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Performance analysis of a dual loop thermally regenerative electrochemical cycle for waste heat recovery

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ABSTRACT

A DLTREC (dual loop thermally regenerative electrochemical cycle) system consisting of two hot electrochemical cells and a cold one is proposed for harvesting waste heat in a more efficient manner. With the maximum power output as the objective function, an optimal analysis of the DLTREC system based on a GA (genetic algorithm) method was conducted for different inlet temperatures of the heat source. For comparison, an optimization analysis of conventional TREC (thermally regenerative electrochemical cycle) systems was also conducted under equivalent criterion. The maximum output, the corresponding electrical and exergy efficiencies, and exergy destruction of the two energy harvesting systems were analyzed and compared. Results revealed that the DLTREC system can increase the power output and decrease the irreversibility. For the prescribed heat source inlet temperature of 393.15 K, the maximum power output of the DLTREC system was 50.11% larger than that of the conventional TREC system and the electrical efficiency was improved by 13.31%. The exergy efficiency of the DLTREC system was 19.41% larger than that of a conventional TREC system.

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1. Introduction

In the past few decades, harvesting low-grade waste heat has received increasing attention. Many practical methods have been adopted for this objective. Thermodynamic cycles converting low grade thermal energy into electricity, such as the ORC (organic Rankine cycle), Kalina cycle, supercritical CO_2 cycle, and heat pipe technology have been extensively investigated for waste heat recovery and have been implemented for the recovery of low-grade thermal energy from various sources, including solar energy, exhaust gas from internal combustion engines, and geothermal sources [1–5]. Recently, electrochemical heat engines have been attracting more and more attention. In these engines, electrochemical reactions take place at different temperatures, resulting in electricity being generated from the energy difference between those two processes.

Generally, a single cycle is not able to efficiently recover the low-grade waste heat in a practical manner. Therefore, dual or combined cycles have been proposed for optimum recapturing utilization of waste heat. Meinel et al. [6] developed a two-stage ORC with internal heat recovery, in which the thermal efficiency was improved by 2.64%. Wang et al. [7] developed a novel system combining a dual loop ORC with a gasoline engine in which the thermal efficiency was increased by 3–6%. Shi et al. [8] researched a combined system, which consists of an ammonia–water mixture Rankine cycle and a LNG (liquefied natural gas) power generation cycle. Kong et al. [9] studied an energy system consisting of a gas turbine, an absorption chiller, and a heat recovery boiler. Li et al. [10] proposed a parallel double-evaporator ORC with the aim of decreasing system irreversibility and enhancing power output. Meng et al. [11] investigated the integration of a metal hydride system with a natural gas liquefier cycle plant for the cascade utilization of LNG (liquefied natural gas). Li et al. [12] investigated a new compound system that combined an ORC plant with a GHT (gathering heat tracing) station and an oil recovery system. Fu et al. [13] compared a Kalina cycle-based cascade utilization system to an existing ORC-based geothermal power system in an oilfield.

Additionally, thermoelectric materials and devices have been studied extensively in the past few decades [14–19]. Electrochemical heat engines offer an alternative method for the conversion of heat into electricity; one of which is the TREC (thermally regenerative electrochemical cycle). The TREC, which is a Stirling-like cycle, exhibits an efficiency of 40–50% of the Carnot limit for

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high-temperature applications [20]. Recently, some literature has been concentrated on the application of applying TREC in harvesting low-grade thermal energy [21]. Based on finite time thermodynamics [22–25], the performance of the TREC has been systematically investigated [26]. Lee et al. [27] conducted an experiment on an electrochemical system for the efficient harvesting of low-grade heat energy. They found that the electrical efficiency reaches 5.7% when cycled between 10 and 60 °C. Yang et al. [21] proposed a charging-free TREC system, and an electrical efficiency of 2.0% was achieved for the TREC when operating between 20 and 60 °C. In addition, a membrane-free battery for the TREC was also been investigated resulting in an electrical efficiency of 3.5% when the battery was discharged at 15 °C and recharged at 55 °C [28]. Long et al. [29] adopted the TREC to harvest waste heat from the PEMFC (proton exchange membrane fuel cell), and found that 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%. In his later research, multi-objective optimization of a continuous TREC for waste heat recovery has also been conducted [30].

In this study, in order to recover waste heat more efficiently, a DLTREC (dual loop thermally regenerative electrochemical cycle) system is proposed. This system consists of two electrochemical cells exchanging heat with the heat source and one cell exchanging heat with the cold source, resulting in more heating being absorbed and more electricity being generated. With the maximum power output as the objective function, the DLTREC system was optimized under different heat source inlet temperatures. In addition, for comparison purposes, optimization of a conventional TREC system with the same objective function was also conducted. The maximum output, the corresponding electrical efficiency, exergy efficiency, and exergy destruction of the conventional and the DLTREC systems were analyzed and compared. The optimal open circuit voltages and current densities of the two systems were also analyzed.

2. Mathematical model of the DLTREC

The schematic diagram for the conventional TREC system is shown in Fig. 1. It contains two cells: a hot cell in contact with the heat source and a cold cell in contact with the cold source (for this study; cold water). Both the cells, in which the electrochemical reactions take place, also function as heat exchangers. The electrolyte solution was cycled through the two cells. A separator was placed inside the cell to conduct ions and prevent the reactants from spontaneously mixing as well as to prevent them from reacting without exchanging electrons through the external circuitry [31]. The TREC consists of four processes: heating, charging, cooling, and discharging. Because of the difference between the charging voltage and the discharging voltage, a net work equal to the difference between the charging and discharging energies is extracted.

In order to recapture the waste heat more efficiently, a DLTREC (dual loop thermally regenerative electrochemical cycle) system is proposed. As shown in Fig. 2, the thermal energy is first utilized by the upstream cell (HC1) and then by the downstream cell (HC2). To reduce the heat loss and to enhance the system efficiency, two regenerators were implemented. The electrolyte solution separates into two streams. One flows into HC2 and the other flows into HC1, where the electrochemical reaction takes place and the heat is absorbed. The electrolyte solution flows out of the cells, mixes in the mixer, and then goes into the CC (cold cell) where the electrochemical reaction takes place and heat is rejected. The schematic circuit diagrams of the conventional and DLTREC systems can be seen in Fig. 3. For the conventional TREC system, the current in the hot cell is equal to that in the cold one. As for the DLTREC system, the current in the cold cell is the sum of those in the two hot cells.

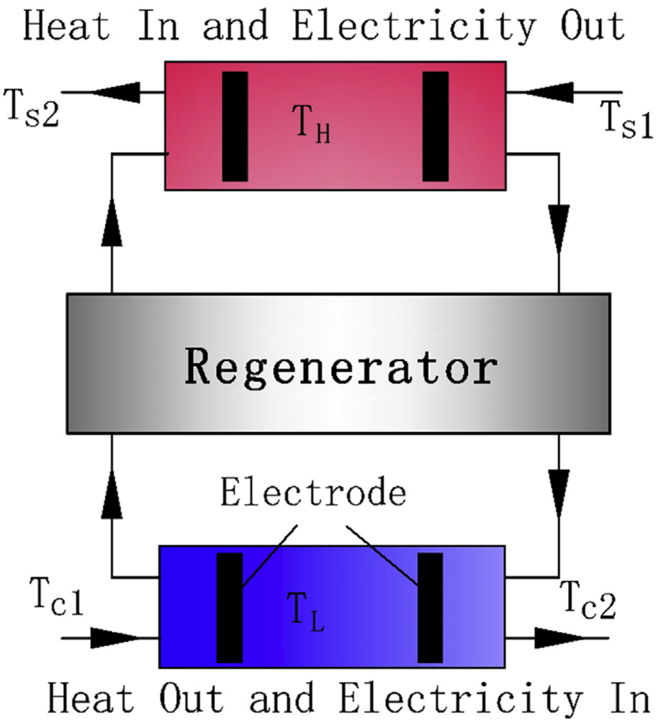

Fig. 1. Schematic of the conventional TREC system.

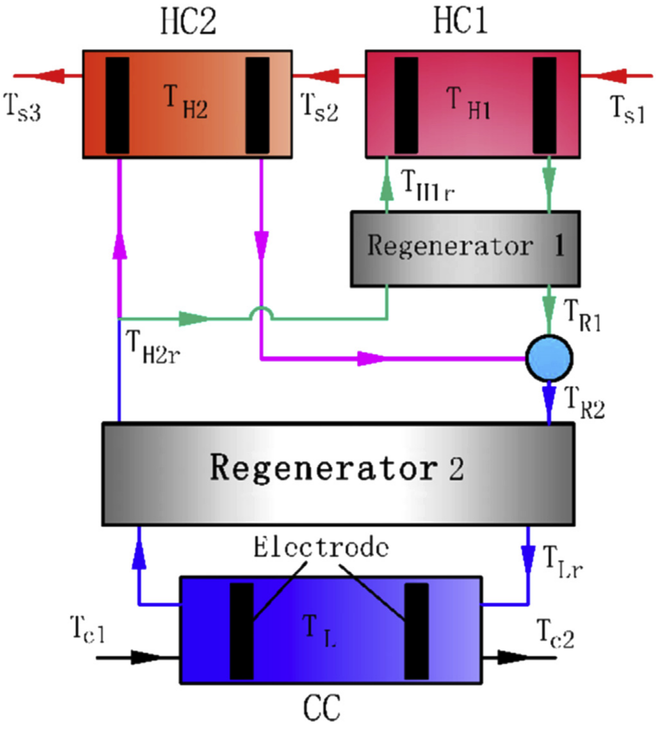

Fig. 2. Schematic of the proposed DLTREC system.

In an electrochemical reaction, an isothermal temperature coefficient may be defined when both electrodes are at the same temperature. For a full cell with an electrode reaction$\Sigma A \rightarrow \Sigma B$, the spontaneous reaction in the isothermal cell can be written

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