Energy 93 (2015) 1022–1029

Contents lists available at ScienceDirect

Energy

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

Multi-objective optimization of a continuous thermally regenerative electrochemical cycle for waste heat recovery

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ARTICLE INFO

Article history:
Received 14 July 2015
Received in revised form
31 August 2015
Accepted 22 September 2015
Available online 22 October 2015

Keywords:
Multi-objective optimization
Maximum power output
Maximum exergy efficiency
TREC (Thermally regenerative electrochemical cycle)

ABSTRACT

An optimization analysis of a continuous TREC (thermally regenerative electrochemical cycle) was conducted with maximum power output and exergy efficiency as the objective functions simultaneously. For comparison, the power output, exergy efficiency, and thermal efficiency under the corresponding single-objective optimization schematics were also calculated. Under different optimization methods it was observed that the power output and the thermal efficiency increase with increasing inlet temperature of the heat source, whereas the exergy efficiency increases with increasing inlet temperature, reaches a maximum value, and then decreases. Results revealed that the optimal power output under the multi-objective optimization turned out to be slightly less than that obtained under the single-objective optimization for power output. However, the exergy and thermal efficiencies were much greater. Furthermore, the thermal exergy and exergy efficiency by single-objective optimization for energy efficiency shows no dominant advantage than that obtained under multi-objective optimization, comparing with the increase amplitude of the power output. This suggests that the multi-objective optimization could coordinate well both the power output and the exergy efficiency of the TREC system, and may serve as a more promising guide for operating and designing TREC systems.

1. Introduction

Because of growing concerns about energy consumption and sustainable development, solutions based on thermodynamic cycles address these issues by efficiently converting low-grade waste heat into electricity. Traditional cycles such as the ORC (organic Rankine cycle), Kalina cycle, supercritical CO_2 cycle, and heat pipe technology have been extensively investigated in recent years [1–10]. In addition, novel thermoelectric devices have also been utilized to harvest low-grade thermal energy, i.e., TREC (thermally regenerative electrochemical cycles), thermoelectric devices, and pyroelectric applications [11–14]. Additionally, much effort has been devoted to optimizing the performance of these cycles and devices to meet actual demand.

Maximum power output is usually chosen as the key metric in evaluating a heat recovery system. Much literature has focused on obtaining the optimal configurations of different heat recovery systems with maximum power as the objective function. Soffiato et al. [15] conducted an optimization procedure of ORC systems for waste heat recovery on board a LNG carrier with the aim of maximizing power output. Under the same criterion, an innovative ORC power plant layout for heat and power generation from medium to low-temperature geothermal resources was developed [16]. In addition, exergy analysis could also provide insights into the system's degree of thermodynamic perfection and the quantitative magnitudes of irreversibility. Xi et al. [17] chose exergy efficiency as the objective function in optimizing a regenerative ORC. Zhu et al. [18] investigated the exergy destruction and the exergy flow map of a bottoming ORC to recover waste heat from the engine exhaust gas. Additionally, the exergy destruction in each component and the exergy efficiency of the ORC system was also studied by Kaska [19], Sun et al. [20] and Borsukiewicz-Gozdur [21]. Many other criteria have been adopted to study heat harvesting systems, such as the ratio of net power output to the total heat transfer area [22], life-cycle evaluation [23,24], and thermo-economic criterion [25–28].

However, when optimizing a system, the objective functions, such as maximum power and maximum thermal efficiency or maximum power and minimum cost may be at conflict with one another. In order to achieve an optimum solution for the conflicting

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http://dx.doi.org/10.1016/j.energy.2015.09.098
0360-5442/

objectives, multi-objective optimization for energy harvesting systems based on NSGA-II algorithms has been extensively investigated [29–32]. Haghighat et al. [33] conducted a multi-objective optimization of integrated high-temperature MCFC-GT (molten carbonate fuel-cell gas turbines) and ORC systems with two conflicting objectives including total exergetic efficiency and the total cost of the system. Imran et al. [34] optimized the evaporator of an ORC for low temperature geothermal heat sources to minimize costs and pressure drop. Additionally, multi-objective optimization for different kinds of refrigerators and heat pumps has also been investigated [35,36].

Recently, the application of TREC systems in the harvesting of low-grade thermal energy has drawn some attention [37,38]. Lee et al. [39] conducted an experiment on an electrochemical system for the efficient harvesting of low-grade heat energy, and found that electrical efficiency reaches 5.7% when cycled between 10 and 60 °C. While most TREC systems still require external electricity for charging, Yang et al. [37] proposed a charging-free TREC system. The two electrochemical processes at both low and high temperatures in a cycle are discharging. An electrical efficiency of 2.0% was achieved for the TREC system operating between 20 and 60 °C. In addition, a membrane-free battery for the TREC system was also investigated [40]. An electrical efficiency of 3.5% was obtained for this method when the battery discharged at 15 °C and recharged at 55 °C. However, a continuous flow process could achieve a larger temperature lift than a batch process by using two electrochemical cells at different temperatures and by exchanging heat between the working substance as it is pumped between the cells [41].

As to investigating the performance of the TREC system, much literatures have been focused on selecting the electrode materials. Few efforts have been dedicated to studying the optimal configurations of TREC system and its thermodynamic performance. In this study, we conducted an optimization of a continuous TREC system for different heat source inlet temperatures with maximum power output and exergy efficiency as the objective functions. Because the power output and exergy efficiency cannot achieve their maximum values simultaneously, an NSGA-II algorithm was adopted as the optimizing method. A TOPSIS (technique for order preference by similarity to an ideal solution) decision making method was utilized to identify the final optimal design point of the system. The power output and exergy efficiency of the TREC system under optimal conditions was investigated. The corresponding thermal efficiency and exergy destructions of the TREC system were also analyzed. Furthermore, the power output, exergy efficiency, and thermal efficiency of the TREC system under single-objective function conditions were also compared. Lastly, some conclusions were drawn.

2. Mathematical model of the continuous TREC

The schematic for a continuous TREC system is shown in Fig. 1. It contains two cells: a hot cell in contact with the heat source 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 is cycled through the two cells. A separator is placed inside the cell to conduct ions and to prevent the reactants from spontaneously mixing and reacting without exchanging electrons through the external circuitry [41]. The corresponding T–S diagram is shown in Fig. 2. The TREC consists of four processes: heating, charging, cooling, and discharging. Because of a 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 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 as $\sum v_j C_j = 0$, where C_j is the jth chemical involved and v_j is its stoichiometric number. The isothermal coefficient for the full cell can be defined as [42]

$$\alpha_c = \left(\frac{\partial V_{oc}}{\partial T}\right)_{iso,T} = \frac{\sum v_j s_j}{nF} = \frac{\Delta \dot{s}}{nF}, \tag{1}$$

where V_{oc} is the open circuit voltage of the full cell in the isothermal condition. s_j is the partial molar entropy of the jth chemical involved, n is the number of moles of electrons passed per v_j mole of C_j reacted, and F is the Faraday constant. Therefore in the charging and discharging processes, the open circuit voltage are, respectively, given by $V_H = \alpha_c T_H$ and $V_L = \alpha_c T_L$.

Taking into account the losses due to the internal resistance, the voltage output is

$$V = V_H - V_L - 2IR_{int}, \tag{2}$$

where R is the resistance of each cell. $I = iA$ is the current. i is the current density, and A is the active surface.

The power output is given by

$$P = IV = I(V_H - V_L) - 2I^2 R_{int} \tag{3}$$

and the change in Gibbs free energy during the charging process is

$$\Delta G_H = \Delta H_H - T_H \Delta \dot{S}_H \tag{4}$$

where ΔH_H is the enthalpy change of the electrolyte solution in the charging process. This value can be ignored because of the nearly unchanged heat capacity of the electrolyte solution [39], which results in $\Delta G_H = -T_H \Delta \dot{S}_H$.

Therefore, the reversible heat absorbed during the charging process is

$$\dot{Q}_H = T_H \left|\Delta \dot{S}_H\right| = |\Delta G_H|. \tag{5}$$

A regenerator is employed in order to enhance the efficiency. The regenerative heat loss per cycle, denoted by ΔQ_{re}, is given by

$$\Delta \dot{Q}_{re} = c_p \dot{n}_{es} (1 - \eta_{re})(T_H - T_L), \tag{6}$$

where c_p is the molar specific heat of the electrolyte solution; η_{re} is the regenerative efficiency; and $\dot{n}_{es} = I/\varphi nF$ is the molar flow rate. φ is the molar percentage of the reactant in the electrolyte solution. Because the heat generated by the resistance is also absorbed by the cell, the total heat absorbed from the heat source is then

$$\dot{Q}_{Total} = \dot{Q}_H + \Delta \dot{Q}_{re} - I^2 R_{int} \tag{7}$$

and the thermal efficiency is

$$\eta_{th} = P \Big/ \dot{Q}_{Total} \tag{8}$$

The exergy losses in each of the processes may also be calculated as follows.

Exergy destruction in the hot cell:

$$\dot{I}_{HC} = T_0 \left[\dot{n}_{es} c_p \lg \frac{T_2}{T_{2r}} + \Delta \dot{S}_H - \frac{I^2 R_{int}}{T_H} - \dot{m}_{hs} \left(s_{hs,in} - s_{hs,out}\right)\right]. \tag{9}$$