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Ecological analysis of a thermally regenerative electrochemical cycle

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ABSTRACT

The performance of a TREC (thermally regenerative electrochemical cycle) has been investigated based on the finite time analysis. The impacts of the cell material, heat exchangers, and heat sources on the maximum ecological objective function and its corresponding power output and efficiency have been analyzed. For prescribed heat sources, the efficiency corresponding to the maximum ecological criterion is always less than that corresponding to the maximum power. Results also reveal that materials with larger isothermal coefficient and specific charge/discharge capacity and lower internal resistance and specific heat lead to a larger maximum ecological objective function and the corresponding power output and efficiency. Heat exchangers with much higher performance are of no practical use to enhance the performance of the TREC system, and the characteristics of the heat sources also present significant impacts on the performance of the TREC under the maximum ecological criterion. As the ecological criterion considers both the energy benefit and loss, the results in this paper may contribute in designing high performance TREC devices.

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1. Introduction

The utilization of low-grade waste heat has attracted much interest following concerns regarding the shortage of fossil energy, the depletion of fossil fuels, and global warming. Thermodynamic cycles such as the ORC (organic Rankine cycle), Kalina cycle, supper critical CO_2 cycle, Stirling engine and those involving heat pipe technology and TE (thermoelectric) devices can alleviate such issues by converting low-grade heat resources into electricity [1–7]. For optimizing the performance of those cycles, MP (maximum power) output is the main figure of merit. Considering finite time durations of the heat transfer processes between heat reservoirs and working fluid, Curzon-Ahlborn [8] proposed the concept of endoreversible Carnot heat engine, and deduced its efficiency at maximum power output. That is the well-known CA efficiency $\eta_{CA} = 1 - \sqrt{T_c/T_h}$. It opens the era of finite time thermodynamics [9,10]. Based on the CA model, by considering different heat transfer laws between the working medium and the heat reservoirs and the internal dissipations, many revisions have been made to describe the real life heat engines more accurately, and some good results have also been obtained [11–19]. However, actual heat engines may not work in the MP condition, but under a compromise between energy benefits and losses. Angulo-Brown [20] proposed an optimization criterion for Carnot heat engines as $E = \dot{W} - T_c\dot{\sigma}$ to consider both the energy benefits and losses, where $\dot{W}$ is the power output, and $\dot{\sigma}$ is the entropy production rate. Actually it is the Ω criterion for heat engines defined later by Hernández et al. [21]. Based on the Ω criterion, de Tomas et al. [22] and Long et al. [23] obtained the efficiency bounds of the heat engines through the low dissipation model and the minimally nonlinear irreversible model. To step further, Yan [24] declared that it is more reasonable to use $E = \dot{W} - T_0\dot{\sigma}$ for heat engines, representing the best compromise between the power output $\dot{W}$ and the power loss $T_0\dot{\sigma}$, which stems from entropy generation in the system and its surroundings, where T_0 is the temperature of the ambient. Many researches had been focused on the irreversible Carnot heat engines under the ecological optimization criterion [25–32]. And the ecological criterion has also been applied to optimize some practical cycles, such as Stirling engine [33], Brayton cycle [26,34–36], and even the quantum heat engines [37]. Yasin et al. [35] conducted a performance analysis based on an ecological performance criterion for an endoreversible regenerative Brayton heat-engine. Abdul et al. [38] ecologically optimized the power output of an endoreversible and regenerative gas-turbine power-cycle for infinite thermal-capacitance rates to and from the reservoirs. Based on the exergy-based ecological criterion, Chen et al. [29] studied a class of generalized irreversible universal steady-

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flow heat-engine cycle models consisting of two heating branches, two cooling branches and two adiabatic branches with the consideration of the losses of heat-resistance, heat leak and internal irreversibility. Furthermore, under the ecological criteria, the performance of many other thermodynamic cycles has also been systematically investigated [39,40].

For energy harvesting, thermoelectrics is a promising technology, however the main disadvantage is the relatively low conversion efficiency and figure-of-merit (ZT) compared to other technologies [41], and the value of ZT is usually less than 2 [42]. What is more, the Seebeck effect in an electrochemical system has also been investigated for energy harvesting systems; the problem is that its efficiency achieved is much lower than the corresponding Carnot efficiency [43,44]. An alternative approach to an electrochemical system for thermal energy harvesting is to explore a thermodynamic cycle as a heat engine. An electrochemical cycle based on the thermogalvanic effect and temperature dependence of electrode potential has been proposed: discharging a battery at temperature T_H and charging back at temperature T_L [45]. If the charging voltage at T_L is lower than the discharging voltage at T_H, net energy is produced by the voltage difference that originates from heat absorbed at the higher temperature. To enhance the efficiency, regenerators have been adopted as in the case of Stirling engines. This is the TREC (thermally regenerative electrochemical cycle), which shows an efficiency of 40–50% of the Carnot limit for high-temperature applications [43]. Recently, TREC has been applied to recovery low-grade thermal energy. Long et al. [46] 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%. Lee et al. [44] 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. Yang et al. [47] proposed a charging-free TREC system, and the electrical efficiency of 2.0% is reached for the TREC operating between 20 and 60 °C. Besides, a membrane-free battery for the TREC has been also investigated [48]. Furthermore, multi-objective optimization of a continuous TREC for waste heat recovery has been conducted [49], and the refrigeration system based on reversed TREC has also been studied [50].

However, most the aforementioned literature about the TREC are dedicated to studying the maximum efficiency the TREC can achieve by investigating high performance electrode materials. As a thermodynamic cycle, its performance has not been widely studied. Finite time thermodynamics could offer an alternative method to investigate the performance of the TREC with irreversibility. In this paper, we conduct an analysis of the TREC with imperfect regenerator, internal dissipations and finite heat capacity of external reservoirs based on the ecological criterion. The analytic expressions of the ecological objective function have been deduced. And the impacts of the cell material, heat exchangers and the heat source on the maximum ecological criterion and the corresponding power and efficiency have been studied. And some useful results have been drawn for TREC devices.

2. Mathematical model

As shown in Fig. 1, the TREC consists of four processes: heating, charging, cooling, and discharging. In processes 1–2, the cell is heated from T_L to T_H under an open circuit condition. The cell is then charged at a lower voltage at T_H in process 2–3, and the entropy of the cell increases through heat absorption during the electrochemical reaction. In process 3–4, the cell is cooled down from T_H to T_L in the open circuit state, thus increasing the open circuit voltage. In the final process (4–1), the cell is discharged at a higher voltage at T_L and the entropy of the cell increases though the ejection of heat into the cold reservoir. After the cycle, the cell returns to its initial state. Furthermore, as the TREC is a Stirling-like cycle, a regenerator should also be adopted to improve its performance, as depicted in Fig. 1. Since the charging voltage is lower than the discharging voltage, the net work (W) equal to the difference between charging and discharging energy is extracted.

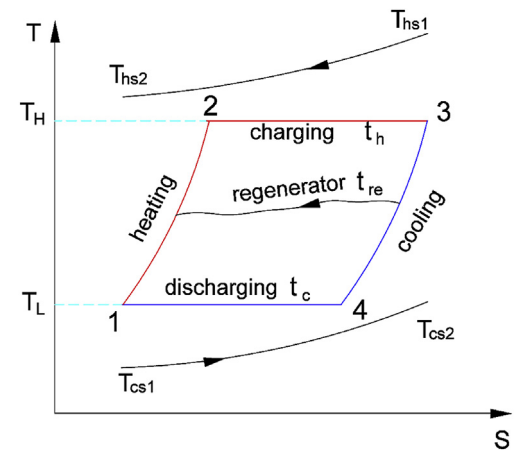

Fig. 1. Schematic T-S diagram for the TREC.

In an electrochemical reaction, an isothermal temperature coefficient may be defined when both electrodes are at the same temperature. The isothermal coefficient for the full cell can be defined as [51]

$$\alpha_c = \left(\frac{\partial V_{oc}}{\partial T}\right)_{\text{iso}}, \tag{1}$$

where V_{oc} is the open circuit voltage of the full cell in the isothermal condition. α_c has opposite signs in the charging and discharging processes. For a full cell with an electrode reaction $\Sigma A \rightarrow \Sigma B$, the spontaneous reaction in the isothermal cell can be written as $\sum \nu_j C_j = 0$, where C_j is the jth chemical involved and ν_j is its stoichiometric number. ν_j is positive for A and negative for B. We then obtain

$$\alpha_c = \left(\frac{\partial V_{oc}}{\partial T}\right)_{\text{iso}} = \frac{\sum \nu_j s_j}{nF}, \tag{2}$$

where s_j is the partial molar entropy of the jth chemical involved, n is the number of moles of electrons passed per ν_j mole of C_j reacted, and F is the Faraday constant. The entropy change of the charging process at T_H can thereby be expressed as

$$\Delta S_H = \int_{\text{i}}^{\text{f}} \sum s_j dn_j, \tag{3}$$

where i and f represent the initial state (ΣA) and the final state (ΣB), respectively. It is well known in physical chemistry that the extent of reaction is equal for all chemicals involved in the reaction, as $\xi = (n_j - n_{j0})/\nu_j$, where n_{j0} is the amount of jth chemical at the initial state, and n_j is the amount of jth chemical at a certain time during the reaction. The substitution of Eq. (2) into Eq. (3) yields

$$\Delta S_H = \int_i^f d\xi \sum v_j s_j = \int_i^f \alpha_c nF d\xi = \overline{\alpha}_c nF \int_i^f d\xi. \tag{4}$$

As α_c is nearly constant in the range of charge and discharge, we can apply the approximation $\overline{\alpha}_c = \alpha_c$, leading to $\Delta S_H = m\alpha_c q_{c_c h}$, where m is the mass of the cell and $q_{c_c h}$ is the specific charge capacity. $mq_{c_c h}$ is the total amount of charge transferred in the charging process at T_H. The heat absorbed during the charging process is

$$Q_H = T_H \Delta S_H = m\alpha_c T_H q_{c_ch}. \tag{5}$$

Similarly, the heat released during the discharging process at T_L is

$$Q_L = T_L \Delta S_L = m\alpha_c T_L q_{c_dis}. \tag{6}$$

where q_{c_dis} is the specific charge capacity at temperature T_L. Here, we assume $q_{c_ch} = q_{c_dis} = q_c$. Furthermore, if charging and discharging processes are assumed to be constant current processes, then the currents are, respectively, given by $I_{ch} = mq_c/\tau_h$, $I_{dis} = mq_c/\tau_c$, with τ_h and τ_c being the durations of the charging and discharging processes. Therefore, total energy loss due to the internal resistances during the charging and discharging processes is given by

$$E_{loss} = I_{ch}^2 R_{ch} \tau_h + I_{dis}^2 R_{dis} \tau_c, \tag{7}$$

where R_{ch} and R_{dis} are the internal resistances corresponding to the charging and discharging processes, respectively. If the internal resistance in each of the processes is equal, that is $R_{ch} = R_{dis} = R_i$, we have

$$E_{loss} = I_{ch}^2 R_{ch} \tau_{ch} + I_{dis}^2 R_{dis} \tau_{dis} = m^2 q_c^2 R_{int} (1/\tau_h + 1/\tau_c). \tag{8}$$

The entropy generation due to the dissipation by the internal resistance is

$$S_{int} = \frac{I_{ch}^2 R_{ch} \tau_h}{T_H} + \frac{I_{dis}^2 R_{dis} \tau_c}{T_L} = m^2 q_c^2 R_{int} (1/T_H \tau_h + 1/T_L \tau_c), \tag{9}$$

Therefore, during a cycle the total work output can be expressed as

$$W = Q_H - Q_L - E_{loss}. \tag{10}$$

On the other hand, the heat absorbed from the hot reservoir and the heat released to the cold reservoir can respectively be expressed as

$$Q_H = K_h (LMTD)_h \tau_h = C_h (T_{hs1} - T_{hs2}) \tau_h, \tag{11}$$

$$Q_L = K_c (LMTD)_c \tau_c = C_c (T_{cs2} - T_{cs1}) \tau_c, \tag{12}$$

where C_h and C_c are the heat capacitance rates of the hot and cold reservoirs. T_{hs1} and T_{hs2} are the inlet and outlet temperatures of the hot reservoir, respectively. Similarly, T_{cs1} and T_{cs2} are the inlet and outlet temperatures of the cold reservoir. K_h and K_c are the heat conductances on the hot and cold reservoir sides. The logarithmic mean temperature differences $(LMTD)_h$, $(LMTD)_c$, respectively, can be defined as

$$(LMTD)_h = (T_{hs1} - T_{hs2}) \Big/ \ln \frac{T_{hs1} - T_H}{T_{hs2} - T_H}, \tag{13}$$

$$(LMTD)_c = (T_{cs2} - T_{cs1}) \Big/ \ln \frac{T_L - T_{cs1}}{T_L - T_{cs2}}. \tag{14}$$

Using Eqs. (5)–(14), we have

$$T_{hs2} = T_H + (T_{hs1} - T_H)(1 - \phi_h), \tag{15}$$

$$T_{cs2} = T_L - (T_L - T_{cs1})(1 - \phi_c), \tag{16}$$

$$Q_H = C_h \phi_h (T_{hs1} - T_H) \tau_h = \alpha_c T_H m q_c, \tag{17}$$

$$Q_L = C_c \phi_c (T_L - T_{cs1}) \tau_c = \alpha_c T_L m q_c, \tag{18}$$

where T_{hs2}, T_{cs2} are the outlet temperatures of the hot heat source and cold heat source, respectively. ϕ_h and ϕ_c are the effectiveness figures of the hot and cold sides of the heat exchangers and are given as $\phi_h = 1 - e^{-N_h}$ and $\phi_c = 1 - e^{-N_c}$, respectively. $N_h = K_h/C_h$ and $N_c = K_c/C_c$ are the number of heat transfer units. Based on Eqs. (17) and (18), the time durations of the heat absorbing and releasing processes are

$$\tau_h = \frac{\alpha_c T_H m q_c}{C_h \phi_h (T_{hs1} - T_H)} \tag{19}$$

$$\tau_c = \frac{\alpha_c T_L m q_c}{C_c \phi_c (T_L - T_{cs1})}. \tag{20}$$

It is also desirable to consider the finite heat transfer through the regenerator. The regenerative heat loss per cycle, denoted ΔQ_{re}, is proportional to the temperature difference of the cell as given by

$$\Delta Q_{re} = c_p m (1 - \eta_{re})(T_H - T_L), \tag{21}$$

where c_p is the specific heat of the cell and η_{re} is the regenerative efficiency. The entropy generation during the heat transfer processes can be written as

$$S_{heat} = \frac{Q_L + \Delta Q_{re}}{T_{cs}} - \frac{Q_H + \Delta Q_{re}}{T_{hs}} \tag{22}$$

As the specific heat capacities of the heat and cold source can be treated as constants in the studied temperature range, the average temperature of the heat and cold sources can be defined as $T_{cs} = (T_{cs1} + T_{cs2})/2$, $T_{hs} = (T_{hs1} + T_{hs2})/2$. Furthermore, the time taken by the regenerative processes is considered, and is assumed to be proportional to the temperature difference of the working fluid [33,52,53]. Thus,

$$\tau_{re} = \beta_1 (T_H - T_L) + \beta_2 (T_H - T_L) = \beta (T_H - T_L), \tag{23}$$

where β_1 and β_2 are the proportionality constants in the regenerative processes 1–2 and 3–4, respectively, and are independent of the temperature differences but dependent on the property of the regenerative material. We denote $\beta = \beta_1 + \beta_2$. Therefore, the total duration of the cycle can be written as $\tau_h + \tau_c + \tau_{re}$. The power output, efficiency and the ecological objective function are defined as

$$P = \frac{Q_H - Q_L - E_{loss}}{\tau_h + \tau_c + \tau_{re}}, \tag{24}$$

$$\eta = \frac{Q_H - Q_L - E_{loss}}{\Delta Q_{re} + Q_H}, \tag{25}$$

$$E = \frac{W - T_0(S_{heat} + S_{int})}{\tau_h + \tau_c + \tau_{re}}. \tag{26}$$

Based on the aforementioned equations, the power output, efficiency and the ecological objective function can be rewritten as

$$P = \frac{\alpha_c(T_H - T_L) - R_{int}\left(\frac{C_h\phi_h(T_{hs1}-T_H)}{\alpha_c T_H} + \frac{C_c\phi_c(T_L-T_{cs1})}{\alpha_c T_L}\right)}{\frac{\alpha_c T_H}{C_h\phi_h(T_{hs1}-T_H)} + \frac{\alpha_c T_L}{C_c\phi_c(T_L-T_{cs1})} + \frac{\beta}{mq_c}(T_H - T_L)}, \tag{27}$$

$$\eta = \frac{\alpha_c(T_H - T_L) - R_{int}\left(\frac{C_h\phi_h(T_{hs1}-T_H)}{\alpha_c T_H} + \frac{C_c\phi_c(T_L-T_{cs1})}{\alpha_c T_L}\right)}{\frac{c_p}{q_c}(T_H - T_L)(1-\eta_{re}) + \alpha_c T_H}. \tag{28}$$

analyze the performance of the TREC at maximum ecological criterion, we can maximize the ecological objective function with respect to the charging and discharging temperatures, then get the optimal ones by letting $\partial E/\partial T_H = 0$ and $\partial E/\partial T_L = 0$, thereby, the maximum ecological objective function, and its corresponding power output and efficiency. These will be symmetrically investigated in the following parts.

3. Performance analysis for the TREC at the maximum ecological criterion

The equations $\partial E/\partial T_H = 0$ and $\partial E/\partial T_L = 0$ for T_H and T_L, respectively, are transcendental and cannot be solved analytically. Numerical studies have been made to study the impacts of the cell materials and the heat exchangers on the maximum ecological objective function and the corresponding power and efficiency. In

$$E = \begin{cases} \dfrac{\alpha_c(T_H - T_L) - R_{int}\left[\dfrac{C_h\phi_h(T_{hs1}-T_H)}{\alpha_c T_H} + \dfrac{C_c\phi_c(T_L-T_{cs1})}{\alpha_c T_L}\right]}{\dfrac{\alpha_c T_H}{C_h\phi_h(T_{hs1}-T_H)} + \dfrac{\alpha_c T_L}{C_c\phi_c(T_L-T_{cs1})} + \dfrac{\beta}{mq_c}(T_H - T_L)} \\ -T_0\dfrac{R_{int}\left[\dfrac{C_h\phi_h(T_{hs1}-T_H)}{\alpha_c T_H^2} + \dfrac{C_c\phi_c(T_L-T_{cs1})}{\alpha_c T_L^2}\right] + 2\left(\dfrac{\alpha_c T_L + \dfrac{c_p}{q_c}(1-\eta_{re})(T_H-T_L)}{T_L - (T_L - T_{cs1})(1-\phi_c) + T_{cs1}} - \dfrac{\alpha_c T_H + \dfrac{c_p}{q_c}(1-\eta_{re})(T_H-T_L)}{T_H + (T_{hs1}-T_H)(1-\phi_h) + T_{hs1}}\right)}{\dfrac{\alpha_c T_H}{C_h\phi_h(T_{hs1}-T_H)} + \dfrac{\alpha_c T_L}{C_c\phi_c(T_L-T_{cs1})} + \dfrac{\beta}{mq_c}(T_H - T_L)} \end{cases} \tag{29}$$

According to Eqs. (27)–(29), for general situations with prescribed cell material and heat sources, as depicted in Fig. 2, the ecological objective function and power output of the TREC both exhibit maximum values. The efficiency corresponding to the maximum ecological criterion is always less than that corresponding to the maximum power. The regenerator efficiency has no impact on the maximum power output, but it obviously affects the maximum ecological objective function as shown in Fig. 2(b). To this section, we set $T_{hs1} = 800$ K, $T_{cs1} = 300$ K, $m = 0.05$ kg, and $\beta = 0.05$ sK^{-1}. The cell parameters are chosen based on the previous paper [44,52]. The heat transfer coefficients are chosen according to Refs. [52,54].

3.1. Impacts of the cell material

According to Eq. (29), the cell material characteristics affecting the ecological performance of the TREC are: the isothermal coefficient, specific charge/discharge capacity, the specific heat, and its

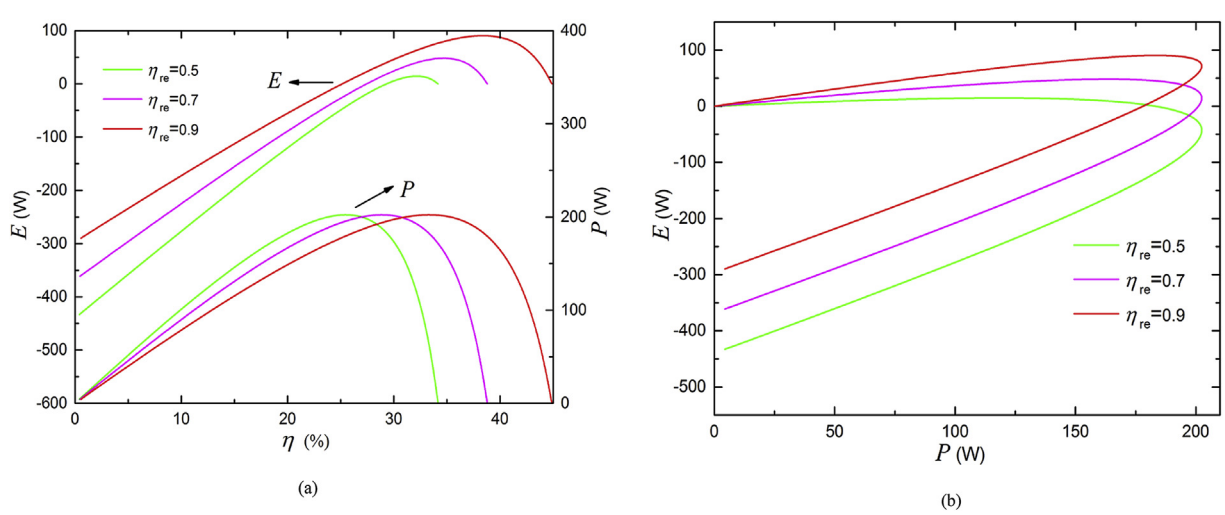

Fig. 2. Ecological objective function and power output versus the efficiency (a), and ecological objective function versus the power output (b) where $\alpha_c = 0.015$ VK^{-1}, $q_c = 20$ mA•hg^{-1}, $c_p = 1.5$ kJ kg^{-1} K^{-1}, $R_{int} = 0.01\ \Omega$, $C_h = C_c = 100$ WK^{-1}, $T_{hs1} = 800$ K, $\phi_h = \phi_c = 0.7$, $T_{cs1} = 300$ K, $m = 0.05$ kg, $\beta = 0.05$ sK^{-1}.

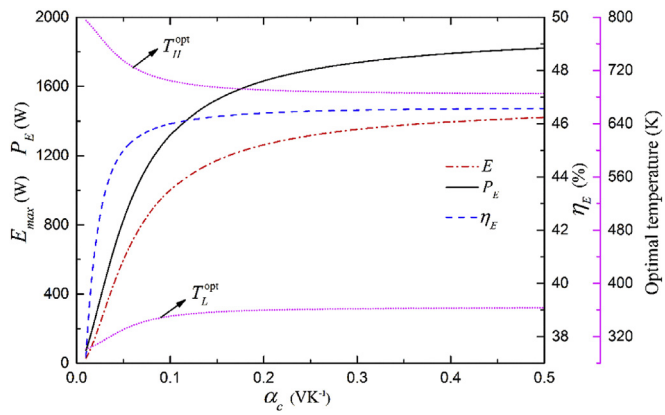

Fig. 3. Maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency as a function of the cell isothermal coefficient, where q_c = 20 mA•hg^{-1}, η_{re} = 0.7, c_p = 1.5 kJ kg^{-1} K^{-1}, R_{int} = 0.01 Ω, $C_h = C_c$ = 100 WK^{-1}, and $\phi_h = \phi_c$ = 0.7.

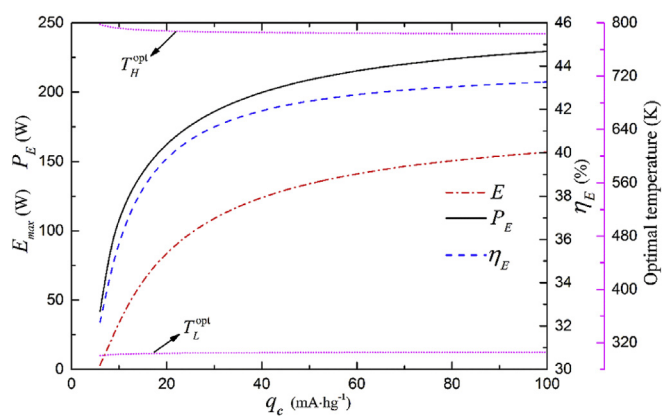

Fig. 4. Curves of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with respect to the specific charge/discharge capacity, where α_c = 0.015 VK^{-1}, c_p = 1.5 kJ kg^{-1} K^{-1}, R_{int} = 0.01 Ω, $C_h = C_c$ = 100 WK^{-1}, $\phi_h = \phi_c$ = 0.7, and η_{re} = 0.7.

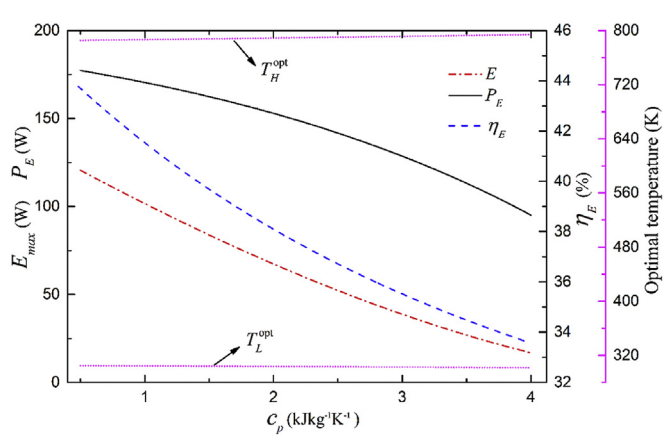

Fig. 5. Curves of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with respect to specific heat, where α_c = 0.015 VK^{-1}, η_{re} = 0.7, q_c = 20 mA•hg^{-1}, R_{int} = 0.01 Ω, $C_h = C_c$ = 100 WK^{-1}, and $\phi_h = \phi_c$ = 0.7.

internal resistance. Of these, the impacts on the maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency are plotted in Figs. 3–6. Under the maximum ecological criterion, the optimal charging temperature decreases with increasing isothermal coefficient, specific charge/discharge capacity and internal resistance, then stays stable; while the discharging temperature presents an opposite trend; the optimal charging temperature decreases with increasing specific heat, then stays stable, specific heat does not obviously impact the optimal discharging temperature. As shown in Fig. 3, the maximum ecological objective function and the corresponding power and efficiency increase with increasing isothermal coefficient. When the isothermal coefficient is larger than a certain value, the efficiency at the maximum ecological objective function remains stable though the maximum ecological objective function and the corresponding power may still increase, but rather slowly. There exists a minimum isothermal coefficient that leads to a maximum efficiency under condition of the maximum ecological objective function. Fig. 4 demonstrates that the maximum ecological objective function and the corresponding power and efficiency increase monotonously with increasing specific charge/discharge capacity. However they decrease monotonously with increasing specific heat as

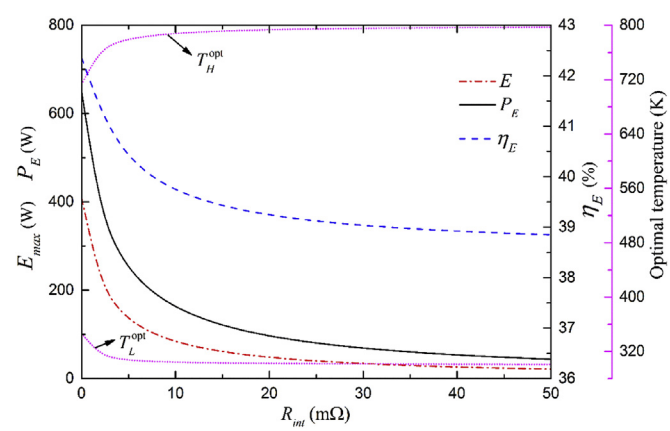

Fig. 6. Curves of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with respect to the internal resistance, where α_c = 0.015 VK^{-1}, η_{re} = 0.7, q_c = 20 mA•hg^{-1}, c_p = 1.5 kJ kg^{-1} K^{-1}, $C_h = C_c$ = 100 WK^{-1}, and $\phi_h = \phi_c$ = 0.7.

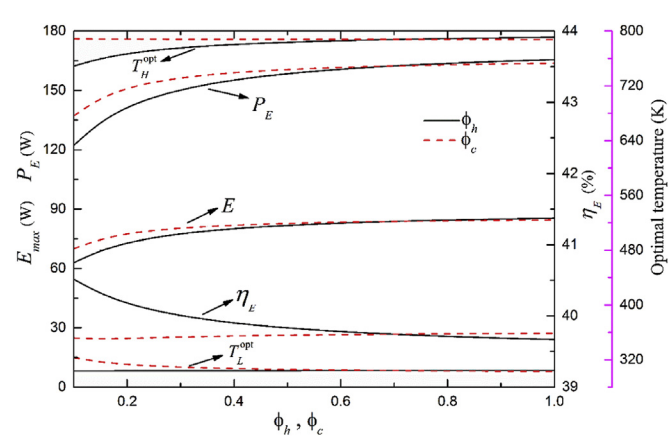

Fig. 7. Curves of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with respect to ϕ_h and ϕ_c, where α_c = 0.015 VK^{-1}, q_c = 20 mA•hg^{-1}, η_{re} = 0.7, c_p = 1.5 kJ kg^{-1} K^{-1}, R_{int} = 0.01 Ω, and $C_h = C_c$ = 100 WK^{-1}.

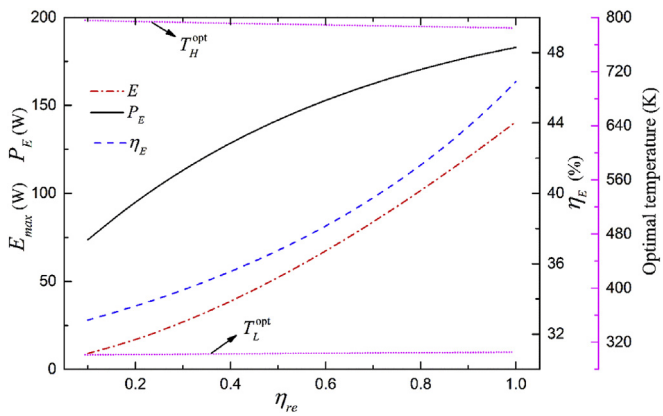

Fig. 8. Curves of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with respect to the regenerative efficiency, where $\alpha_c = 0.015$ VK^{-1}, $q_c = 20$ mA•hg^{-1}, $c_p = 1.5$ kJ kg^{-1} K^{-1}, $R_{int} = 0.01$ Ω, $C_h = C_c = 100$ WK^{-1}, and $\phi_h = \phi_c = 0.7$.

depicted in Fig. 5. The impacts of internal resistance on the maximum ecological objective function and the corresponding power and efficiency are presented in Fig. 6. They decreases sharply with increasing internal resistance. Therefore materials with larger isothermal coefficient and specific charge/discharge capacity, lower internal resistance and specific heat contribute to a better performance for the TREC under the maximum ecological criterion.

3.2. Impacts of the heat exchanger

Based on Eq. (29), the main characteristics impacting the ecological performance of a TREC are the effectiveness (ϕ_h and ϕ_c) of the heat exchangers, the regenerative efficiency and the regenerative duration, whose impacts on the maximum ecological objective function and its corresponding optimal charging/discharging temperatures, power and efficiency are presented in Figs. 7–9. As shown in Fig. 7, under the maximum ecological criterion, the optimal charging temperature increases with ϕ_h, then stays stable; the optimal discharging temperature is not obviously impacted by ϕ_h. However the discharging temperature decreases with increasing ϕ_c, and the charging temperature is nearly not impacted by ϕ_c. According to Eq. (28), in the charging process, the efficiency corresponding to the maximum ecological objective function decreases with increasing ϕ_h, while it is nearly not impacted by ϕ_c in the discharging process, as depicted in Fig. 7. Moreover the maximum ecological objective function and its corresponding power increase with increasing the heat effectiveness of the heat exchangers. When ϕ_h and ϕ_c are larger than a certain value, the maximum ecological objective function and its power increase rather slowly. Therefore exchangers with much higher performance are of no practical use. As the heat exchangers are the main parts of the TREC system, the cost of the installation of a TREC system is much less.

The impacts of regenerative efficiency and the regenerative duration on the optimal charging and discharging temperatures are present in Figs. 8 and 9. The optimal charging temperature decreases slowly with increasing regenerative efficiency, which does not obviously impact the optimal discharging temperature. The optimal charging temperature increases slightly with increasing regenerative duration, which does not obviously impact the optimal discharging temperature. Furthermore, according to Eq. (27), regenerative efficiency has no impact on the power output. However as depicted in Fig. 8, it impacts on the maximum ecological objective function and its corresponding power and efficiency, significantly, which increase monotonously with increasing regenerative efficiency. Larger β implies a longer time interval spent in the regenerator, which leads to better heat exchanging performance of the regenerator in reality, therefore higher efficiency. However, it decreases maximum ecological objective function and its corresponding power extracted, as shown in Fig. 9.

3.3. Impacts of heat sources

The impacts of the heat reservoir temperatures and their heat capacitances (C_h and C_c) on the maximum ecological objective function and its corresponding optimal charging/discharging temperatures, power and efficiency attainable are depicted in Figs. 10–12. Under the maximum ecological criterion, the optimal charging temperature increases with increasing C_h, then stays stable; the optimal discharging temperature is not obviously impacted by C_h. However the discharging temperature decreases with increasing C_c, and the charging temperature is not impacted by C_c. The optimal charging temperature increases obviously with increasing inlet temperature of the heat source, which, however, does not impact the optimal discharging temperature. The impacts of the inlet temperature of the cold source on the optimal charging/

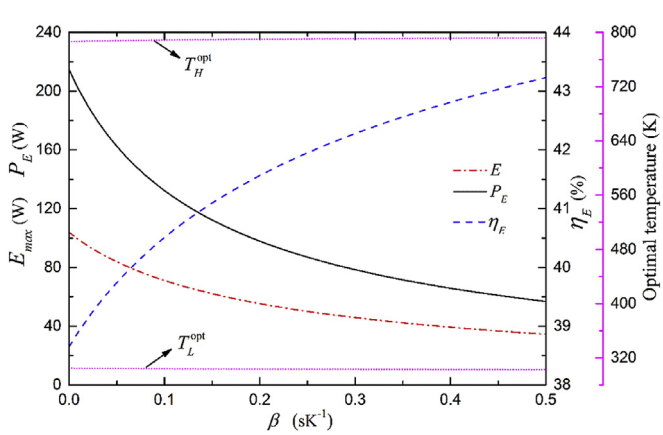

Fig. 9. Curves of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with respect to β, where $\alpha_c = 0.015$ VK^{-1}, $q_c = 20$ mA•hg^{-1}, $\eta_{re} = 0.7$, $c_p = 1.5$ kJ kg^{-1} K^{-1}, $R_{int} = 0.01$ Ω, $C_h = C_c = 100$ WK^{-1}, and $\phi_h = \phi_c = 0.7$.

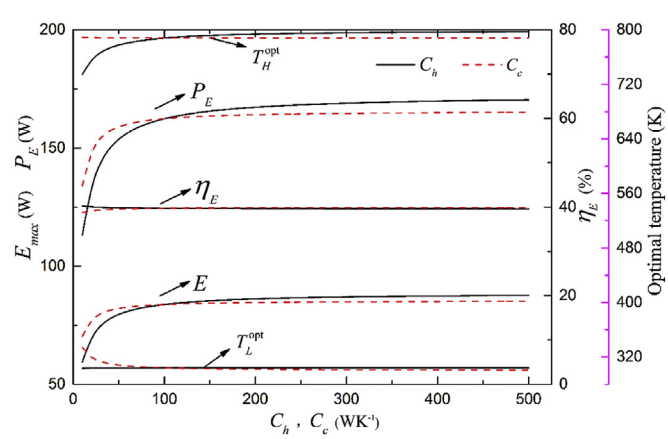

Fig. 10. Variation of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with C_h and C_c, where $\alpha_c = 0.015$ VK^{-1}, $q_c = 20$ mA•hg^{-1}, $c_p = 1.5$ kJ kg^{-1} K^{-1}, $R_{int} = 0.01$ Ω, $\phi_h = \phi_c = 0.7$, and $\eta_{re} = 0.7$.

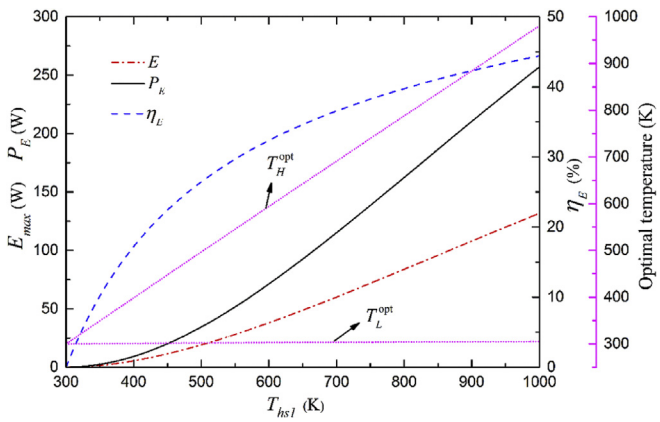

Fig. 11. Variation of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with the inlet temperature of the heat source, where $\alpha_c = 0.015$ VK^{-1}, $q_c = 20$ mA•hg^{-1}, $c_p = 1.5$ kJ kg^{-1} K^{-1}, $R_{int} = 0.01$ Ω, $C_h = C_c = 100$ WK^{-1}, $\phi_h = \phi_c = 0.7$, and $T_{cs1} = 300$ K.

discharging temperatures present an opposite trend. In Fig. 10, maximum ecological objective function and its corresponding power increase with increasing the heat capacitance of the heat source, achieving a maximum value at higher C_h and C_c, displaying saturation afterwards. In the charging process, the efficiency corresponding to the maximum ecological objective function decreases with increasing C_h at very small values of C_h, exhibits a minimum value, thereafter remaining constant, while it increases with increasing C_c at very small values of C_c in the discharging process, attains a maximum value and remains saturated thereafter. It indicates that TREC is very appropriate for harvesting low-grade waste heat. The maximum ecological objective function and its corresponding power and efficiency extracted increase with increasing the inlet temperature of the hot reservoir, and decrease with increasing inlet temperature of the cold reservoir, as shown in Figs. 11 and 12.

4. Conclusion

Under the maximum ecological criterion, the performance of the TREC has been investigated based on finite time analysis. The impacts of the cell material, the heat exchangers (including the regenerator), and the heat sources on the maximum ecological objective function and its corresponding power output and efficiency have been analyzed. For prescribed heat sources, the efficiency corresponding to the maximum ecological criterion is always less than that corresponding to the maximum power. The regenerator efficiency has no impact on the maximum power output, but it obviously affects the maximum ecological objective function.

Materials with large isothermal coefficient and specific charge/discharge capacity and low internal resistance and specific heat lead to a larger maximum ecological objective function and its corresponding power output and efficiency. However under the maximum power output conditions, materials with larger isothermal coefficient and specific charge/discharge capacity, appropriate internal resistance, and lower specific heat are more appealing [52]. Under the maximum ecological criterion, the corresponding power and efficiency exhibit different behaviors with increasing effectiveness of the heat exchangers (ϕ_h and ϕ_c). Larger ϕ_h and ϕ_c lead to a larger power output, however a lower efficiency. When ϕ_h and ϕ_c are larger than a certain value the maximum ecological objective function and its power increase rather slowly. Therefore heat exchangers with much higher performance are of no practical use, which is in accordance with the results obtained under the maximum power output conditions [52]. Less time spent in the regenerator leads to a larger maximum ecological objective function and its corresponding power extracted, albeit with a lower efficiency. The heat source inlet temperature and its capacitance also have considerable impacts on performance of the TREC under the maximum ecological criterion. For higher heat capacitance (the product of mass flow rate and specific heat), the maximum ecological objective function and its corresponding power and efficiency stay constant. It is indicates that TREC is very appropriate for harvesting low-grade waste heat. As the ecological criterion considers the energy benefit and loss, the results in this paper may contribute in designing high performance TREC devices.

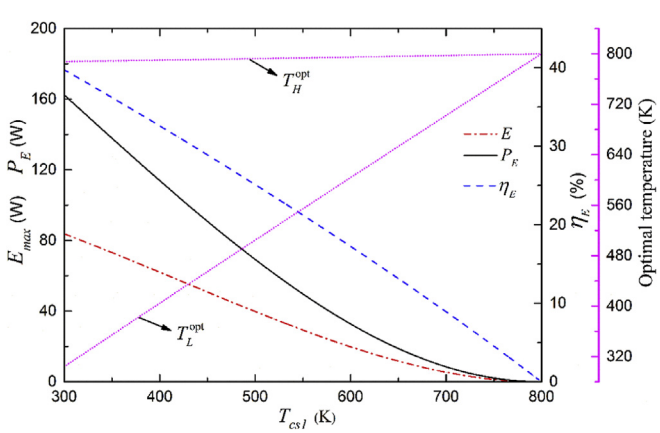

Fig. 12. Variation of maximum ecological objective function and the corresponding optimal charging/discharging temperatures, power and efficiency with the inlet temperature of the cold reservoir, where $\alpha_c = 0.015$ VK^{-1}, $q_c = 20$ mA•hg^{-1}, $c_p = 1.5$ kJ kg^{-1} K^{-1}, $R_{int} = 0.01$ Ω, $C_h = C_c = 100$ WK^{-1}, $\phi_h = \phi_c = 0.7$, and $T_{hs1} = 800$ K.

Acknowledgments

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Nomenclature

α	isothermal coefficients [VK^{-1}]
$\boldsymbol{m}$	mass [kg]
$\boldsymbol{Q}$	heat rate [J]
$\boldsymbol{S}$	entropy [Jkg^{-1} K^{-1}]
$\boldsymbol{T}$	temperature [K]
$\boldsymbol{W}$	work [W]
$\boldsymbol{C_p}$	specific heat [kJ kg^{-1} K^{-1}]
E_{LOSS}	energy loss [J]
q_c	specific charge capacity [mA hg^{-1}]
R	resistance [Ω]
I	currents [A]
τ	time [s]
K	heat conductance [WK^{-1}]
C	heat capacitance rates [Jkg^{-1} K^{-1}]
ΔQ_{re}	regenerative heat loss [J]
P	power [W]
N	number of heat transfer unit
F	Faraday constant

Subscripts

hs	hot reservoir temperature
cs	cold reservoir temperature
H	hot reservoir side

L	cold reservoir side
1	inlet
2	outlet
int	internal
ch	charging process
dis	discharging process
r	regenerator

Greek symbols

η_{re}	regenerative efficiency
η	efficiency
ϕ	heat exchanger effectiveness
β	proportional constant [s^{-1}]

Acronyms

LMTD	logarithmic mean temperature difference

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