Analysis and optimization with ecological objective function of irreversible single resonance energy selective electron heat engines

Junle Zhou^{1,2,3}, Lingen Chen ^{*1,2,3}, Zemin Ding^{1,2,3} and Fengrui Sun^{1,2,3}

1. Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, P. R. China

2. Military Key Laboratory for Naval Ship Power Engineering, Naval University of Engineering, Wuhan 430033, P. R. China

3. College of Power Engineering, Naval University of Engineering, Wuhan 430033, P. R. China)

*To whom all correspondence should be addressed.

E-mail address: lingenchen@hotmail.com and lgchenna@yahoo.com (Lingen Chen)

Fax: 0086-27-83638709 Tel: 0086-27-83615046

Abstract

Ecological performance of a single resonance ESE heat engine with heat leakage is conducted by applying finite time thermodynamics. By introducing Nielsen function and numerical calculations, expressions about power output, efficiency, entropy generation rate and ecological objective function are derived; relationships between ecological objective function and power output, between ecological objective function and efficiency as well as between power output and efficiency are demonstrated; influences of system parameters of heat leakage, boundary energy and resonance width on the optimal performances are investigated in detail; a specific range of boundary energy is given as a compromise to make ESE heat engine system work at optimal operation regions. Comparing performance characteristics with different optimization objective functions, the significance of selecting ecological objective function as the design objective is clarified specifically: when changing the design objective from maximum power output into maximum ecological objective function, the improvement of efficiency is 4.56%, while the power output drop is only 2.68%; when changing the design objective from maximum efficiency to maximum ecological objective function, the improvement of power output is 229.13%, and the efficiency drop is only 13.53%.

Keywords: energy selective electron heat engine, ecological objective function, performance comparison, finite time thermodynamics.

1. Introduction

In the development processes of microelectronic technology, a phenomenon was found that when the electrons are in the process of transmission, the heat transfer is happening at the same

time, which provides a possibility for energy conversion. Therefore, some kinds of micro electronic machine models [1-4] have been put forward. In the year of 2002, based on the theoretical [5] and experimental [6] researches of quantum ratchets, a theoretical model of energy selective electron (ESE) heat engine [7] was established. As one kind of typical micro energy conversion systems, the thermodynamic researches of ESE systems have caused the curiosity of numerous researchers.

With the development of modern thermodynamics, finite time thermodynamics (FTT) theory [8-16] has been a powerful tool for researching optimal performances of various thermodynamic process and cycles [17-19], thermal systems and devices, including two-reservoir Carnot heat engine and refrigeration cycles [20, 21], internal combustion engine cycles [22-25], Stirling engines [26, 27], quantum systems [28-30], nano-scale heat engine cycles [31-34], ESE engine systems [35, 36], thermoelectric devices [37-40] etc. In recent years, with the rapid development of microelectronic technology and nanotechnology, the thermodynamic performance analyses of micro energy conversion systems have been paid much attention. As Andresen [14] once predicted, the optimization with FTT performance in micro energy conversion systems from mesoscopic scale to nanoscale would be the most potential and most probable to make many breakthroughs in the future. So far, many scholars have put FTT theory into the researches of the ESE engine systems, achieved a series of research productions and some powerful conclusions of which can help to design the practical electronic machines. Taking ESE heat engine as example, Humphrey et al. [7] firstly explained the theoretical basis and operation mechanism of the system in detail by comprehensive investigations. Su et al. [41] studied the optimal performance and load matching of a new ESE heat engine model with a variable bias voltage. Luo et al. [42] obtained the variation

regularity, upper and lower limit values of efficiency at maximum power (EMP) by numerical simulations. Ding et al. [43] explored the operation characteristics and optimal performances of ESE system with different transmission probability functions. Yu et al. [44] performed the power and efficiency optimization for an ESE heat engine with double-resonance energy filter, and made a comparison with ESE engine system of single resonance filter.

When analyzing the effects of various irreversibilities on FTT performance, the heat leakage [45, 46] is an irreversibility that can not be neglected. Heat leakage is always considered in kinds of macro energy conversion systems [47-50], for it has great influences on performances of thermal systems. Similar to traditional macro energy conversion systems, heat leakage loss via the phonon transmission process is considered in ESE heat engines [51, 52], ESE refrigerators [53-55] and ESE heat pumps [56, 57], the basic output performances and the influences of heat leakage on performance characteristics are analyzed, which makes the performance analyses be closer to performance characteristics of practical devices.

In order to seek for the optimal performance of a system, an optimal design based on multi-objective optimization method [21, 58-64] was put forward to help to select and determine the optimal choice among different optimization objectives. Since an optimal design is determined by the satisfaction level of multiple targets, making use of multi-objective optimization to explore the optimal thermodynamic performances has been a very active research work in the fields of FTT. In traditional energy conversion systems, except for the regular objective functions of power output, cooling load, heating load, power density and exergy efficiency etc., ecological objective function [65, 66] has also been defined to optimize the thermodynamic performances. Early in the year of 1991, Angulo-Brown [65] originally proposed the ecological objective function for heat

engines, as $E' = P - T_L \sigma$, where P is the power output, σ is the entropy generation rate and T_L is the temperature of the cold reservoir. Yan [66] believed that such an ecological objective had not noticed the essential difference between energy and exergy, and revised the original ecological objective as $E' = P - T_0 \sigma$ (T_0 is the environment temperature), for $T_0 \sigma$ could represent the exergy loss. The newly proposed ecological criterion was thought to be more reasonable for evaluating the thermal cycles, and could make a balanced choice between power output and entropy generation rate. Since ecological objective function was put forward, it has been selected as an objective function to optimize the performance of macroscopic thermal systems, and has experienced considerable development in various thermodynamic cycles and systems. Arias-Hernández and Angulo-Brown [67] early proposed that the endoreversible Carnot-type heat engines have a general property that the efficiency at maximum ecological function is the semisum of the Carnot and the maximum power efficiency for any heat transfer law. Chen et al. [68-70] took the ecological criterion as optimization objective, investigated the optimal ecological performance of generalized irreversible Carnot engines [68], linear phenomenological heat transfer law irreversible Carnot engines [69] and a generalized irreversible Carnot engine working at the maximum ecological objective function [70]. Chen et al. [71] further explored the ecological performance characteristics of a class of universal heat engine cycles include Diesel, Otto, Brayton, Atkinson, Dual and Miller cycles. Long and Liu [72] conducted the efficiency analysis for general heat engines under maximum ecological objective function, obtained the upper and lower bounds of optimal efficiency. Özel et al. [73] developed and compared four new thermoenvironmental evaluation criteria with each other, and concluded that the ecological based ecologicoenvironmental function was defined as the most suitable criteria to evaluate an actual

heat engine. Açıkkalp [74] used five different methods to assess the irreversible Carnot heat engine cycle, and determined that the ecological function was the most advantageous and convenient criteria. For Carnot refrigerators, Açıkkalp [75] presented the exergetic sustainability index to evaluate refrigeration cycle, investigated its relationships with ecological function, and compared the calculation results from the ecological function. Based on a thermo-ecological criterion, Ahmadi et al. [76] and Sahraiea et al. [77] made optimization investigations of a three-heat-source absorption heat pump and a two-stage irreversible heat pump, respectively, and the coefficient of performance and the ecological coefficient of performances were optimized simultaneously. Sadatsakkak et al. [78] optimized an irreversible regenerative closed Brayton cycle by implementing a sophisticated ecological function. Besides the applications in macro thermal systems, ecological objective function has been also widely in quantum systems, ESE systems and other micro systems to analyze the optimal performances. Liu et al. [79, 80] optimized the exergy-based ecological objective function of quantum Carnot heat engines with internal irreversibility. Ding et al. [81] explored the ecological optimization of endoreversible ESE heat engine which worked at different operation regimes. Selecting irreversible double resonance ESE heat engine as research object, Ding et al. [82] made further investigation of the ecological performance, discussed the effects of resonance spacing, resonance width and other parameters on optimal performance of ESE system. It is shown that the systematic ecological optimization is more reasonable for the performance optimization with ESE system, for it may provide beneficial advice for the design of practical ESE machine systems, and ultimately to make the best compromise between exergy benefits and losses.

This paper will adopt the model of a single resonance ESE heat engine with heat leakage in

Ref. [7]. The influences of system parameters on different optimization objective functions and the comparative analyses of the performance characteristics with different optimization objective functions will be investigated in detail. The major and ultimate purpose is to clarify the significance of selecting ecological objective function as the design objective specifically.

2. Model of ESE heat engine with heat leakage

There are two electronic reservoirs and an energy filter in an ESE heat engine model, as shown in Figure 1. The left part is cold electronic reservoir, and the right part is hot electronic reservoir. The temperatures are T_H and T_C , and the electrochemical potentials are μ_H and μ_C , respectively. E' is the boundary energy, and ΔE is the resonance width. With $\mu_C > \mu_H$, the electrons can be exchanged between two reservoirs under the combination of the electrochemical potential gradient (the cold electrons can be transported to hot reservoir from the cold) and the temperature gradient (the hot electrons can be transported to cold reservoir from the hot). In addition, only when energy value E of the electrons meets the requirement of $E' < E < E' + \Delta E$, the electrons can be transported by the energy filter freely. According to Ref. [7], the model can behave as a heat engine when $E > E_0$, where $E_0 = (T_H \mu_C - T_C \mu_H) / (T_H - T_C)$.

From Ref. [7], based on Landauer equation [83] and the first law of thermodynamics, one can obtain the integrals for the heat change of hot and cold reservoirs per unit time with a very narrow energy range δE as

$$\dot{q}_H = \frac{2}{h} (E - \mu_H) (f_H - f_C) \delta E \quad (1)$$

$$\dot{q}_C = \frac{2}{h} (E - \mu_C) (f_H - f_C) \delta E \quad (2)$$

where h is Plank constant, E is the energy of electrons, and f_H and f_C are Fermi distributions of electrons in hot and cold reservoirs,

$$f_H = [1 + \exp(\frac{E - \mu_H}{k_B T_H})]^{-1}, \quad f_C = [1 + \exp(\frac{E - \mu_C}{k_B T_C})]^{-1} \quad (3)$$

where k_B is Boltzmann constant.

Over the entire energy range where ESE heat engine works, the expressions for the heat change in two reservoirs are, respectively

$$\dot{Q}_{HE} = \frac{2}{h} \int_{E'}^{E' + \Delta E} (E - \mu_H)(f_H - f_C) dE \quad (4)$$

$$\dot{Q}_{CE} = \frac{2}{h} \int_{E'}^{E' + \Delta E} (E - \mu_C)(f_H - f_C) dE \quad (5)$$

When the heat leakage loss [45-57] is taken into consideration, it is supposed that the heat leakage obeys the Newtonian heat transfer law, which is defined as

$$\dot{Q}_L = k_L(T_H - T_C) \quad (6)$$

where k_L is thermal conductivity of the filter.

Therefore, one can obtain the total heat releasing rate and total heat absorption rate of hot and cold reservoirs are, respectively

$$\dot{Q}_H = \dot{Q}_{HE} + \dot{Q}_L \quad (7)$$

$$\dot{Q}_C = \dot{Q}_{CE} + \dot{Q}_L \quad (8)$$

In the numerical calculations, it is set in the following equations that $R_H = \frac{E' + \Delta E - \mu_H}{k_B T_H}$, $r_H = \frac{E' - \mu_H}{k_B T_H}$, $R_C = \frac{E' + \Delta E - \mu_C}{k_B T_C}$, $r_C = \frac{E' - \mu_C}{k_B T_C}$, and $g(x) = \text{PolyLog}(2, -x)$, where $\text{PolyLog}(2, -x)$ is the Nielsen function [42].

From Equations (7) and (8), the power output, efficiency and entropy generation rate can be expressed as

$$\begin{aligned} P &= \dot{Q}_H - \dot{Q}_C \\ &= \frac{2}{h} k_B (\mu_C - \mu_H) [T_H \ln \frac{1 + \exp(r_H)}{1 + \exp(R_H)} - T_C \ln \frac{1 + \exp(r_C)}{1 + \exp(R_C)}] \end{aligned} \quad (9)$$

$$\begin{aligned}
\eta &= \frac{P}{\dot{Q}_H} \\
&= (\mu_C - \mu_H) \left[T_H \ln \frac{1 + \exp(r_H)}{1 + \exp(R_H)} - T_C \ln \frac{1 + \exp(r_C)}{1 + \exp(R_C)} \right] / \{ k_B T_H^2 \left[\frac{1}{2} R_H^2 - g(\exp(R_H)) \right. \\
&\quad \left. - R_H \ln(1 + \exp(R_H)) - \frac{1}{2} r_H^2 + r_H \ln(1 + \exp(r_H)) + g(\exp(r_H)) \right] - k_B T_C^2 \left[\frac{1}{2} R_C^2 - \right. \\
&\quad \left. R_C \ln(1 + \exp(R_C)) - g(\exp(R_C)) - \frac{1}{2} r_C^2 + r_C \ln(1 + \exp(r_C)) + g(\exp(r_C)) \right] - T_C \times \\
&\quad \left. (\mu_C - \mu_H) \left[R_C - r_C + \ln \frac{1 + \exp(r_C)}{1 + \exp(R_C)} \right] + (T_H - T_C) \frac{k_L h}{2k_B} \right\} \quad (10) \\
\sigma &= \dot{Q}_C / T_C - \dot{Q}_H / T_H \\
&= \frac{2}{h} k_B^2 \frac{T_H (T_H - T_C)}{T_C} \left[\frac{1}{2} R_H^2 - R_H \ln(1 + \exp(R_H)) - g(\exp(R_H)) - \frac{1}{2} r_H^2 + g(\exp(r_H)) \right. \\
&\quad \left. + r_H \ln(1 + \exp(r_H)) \right] - \frac{2}{h} k_B^2 \frac{T_C (T_H - T_C)}{T_H} \left[\frac{1}{2} R_C^2 - R_C \ln(1 + \exp(R_C)) - g(\exp(R_C)) \right. \\
&\quad \left. - \frac{1}{2} r_C^2 + r_C \ln(1 + \exp(r_C)) + g(\exp(r_C)) \right] - \frac{2}{h} k_B (\mu_C - \mu_H) \left[(R_C - r_C) \left(1 - \frac{T_C}{T_H} \right) + \frac{T_H}{T_C} \times \right. \\
&\quad \left. \ln \frac{1 + \exp(r_H)}{1 + \exp(R_H)} - \frac{T_C}{T_H} \ln \frac{1 + \exp(r_C)}{1 + \exp(R_C)} \right] + (T_H - T_C)^2 \frac{k_L}{T_H T_C} \quad (11)
\end{aligned}$$

For heat engine system, the ecological objective function ECO was defined as

$ECO = P - T_0 \sigma$ [67-74, 78-82], where T_0 is the environmental temperature.

Combining Equation (9) with (11), the expression of ECO is obtained as

$$\begin{aligned}
ECO &= P \left(1 + \frac{T_0}{T_C} \right) - T_0 \left(\frac{1}{T_C} - \frac{1}{T_H} \right) \dot{Q}_H \\
&= \frac{2}{h} k_B (\mu_C - \mu_H) \left[\left(1 + \frac{T_0}{T_C} \right) T_H \ln \frac{1 + \exp(r_H)}{1 + \exp(R_H)} - \left(1 + \frac{T_0}{T_H} \right) T_C \ln \frac{1 + \exp(r_C)}{1 + \exp(R_C)} + T_0 \left(1 - \frac{T_C}{T_H} \right) \times \right. \\
&\quad \left. (R_C - r_C) \right] - T_0 \left(\frac{1}{T_C} - \frac{1}{T_H} \right) \left\{ \frac{2}{h} (k_B T_H)^2 \left[\frac{1}{2} R_H^2 - R_H \ln(1 + \exp(R_H)) - g(\exp(R_H)) - \frac{1}{2} r_H^2 \right. \right. \\
&\quad \left. \left. + r_H \ln(1 + \exp(r_H)) + g(\exp(r_H)) \right] - \frac{2}{h} (k_B T_C)^2 \left[\frac{1}{2} R_C^2 - R_C \ln(1 + \exp(R_C)) - g(\exp(R_C)) \right. \right. \\
&\quad \left. \left. - \frac{1}{2} r_C^2 + r_C \ln(1 + \exp(r_C)) + g(\exp(r_C)) \right] + k_L (T_H - T_C) \right\} \quad (12)
\end{aligned}$$

3. Performance parameters

The parameters are set that $T_0 = 1K$, $T_H = 2.2K$, $T_C = 1.2K$, $\mu_C / k_B = 12K$ and $\mu_H / k_B = 10K$. It can be seen from Ref. [7], when the energy value E of the transmission electrons is adjusted to $E = E_0 = (T_H \mu_C - T_C \mu_H) / (T_H - T_C)$, the efficiency can reach the Carnot efficiency; when $E > E_0$, the system manifests as a heat engine. According to the above

parameters, $E_0 = 14.4k_B$.

Figure 2 shows the relationship between ecological objective function and power output when considering the heat leakage. It is shown that the maximum ecological objective function and the ecological objective function at maximum power output is approximately equal, and the maximum power output is nearly equal to the power output at maximum ecological objective function. Figure 3 shows that the performance curve between ecological objective function and efficiency is loop-shaped one, and the ecological objective function and efficiency can reach their maxima, respectively. It is transparent that with the increase of heat leakage, both the ecological objective function and efficiency decrease.

Figure 4 demonstrates a loop-shaped curve between power output and efficiency. It is not difficult to find that as heat leakage increases, there is no change with maximum power output, but the maximum efficiency decreases, which indicates that the heat leakage has no qualitative effects on the characteristic relation between power output and efficiency, but only has quantitative effects on efficiency. In addition, it can be observed that the optimal operation ranges of ESE heat engine are supposed to be in the $P \sim \eta$ curves where the slope is negative. In these ranges, the efficiency and power output are relatively larger, which are considered as the optimal working regions of ESE heat engine. Taking curve 1 in Figure 4 for example, the optimal working regions are $P_\eta \leq P \leq P_{max}$ and $\eta_p \leq \eta \leq \eta_{max}$.

In order to display the relationships between objective functions and the parameters of boundary energy E' and resonance width ΔE , three-dimensional diagrams of ecological objective function (ECO), power output (P) and efficiency (η) versus E' and ΔE are shown in Figures 5-7. Figures 5-7 suggest that as E' increases, the ECO , P and η increase at first

and then decrease; there exist optimal E'_s to make ECO , P and η reach their maxima, respectively. In addition, the ECO , P and η have similar variation tendency with the increase of ΔE ; there exist optimal ΔE_s to make ECO , P and η reach their maxima, respectively. From Figures 5-7, it can be concluded that the parameters of E' and ΔE is closely related with the performance characteristics of irreversible ESE heat engine. If proper values of the parameters E' and ΔE are selected, ESE heat engine can work at the optimal states of ECO , P and η , respectively.

4. Optimization with ecological objective function

From Equations (12), (9) and (10), the maximum ecological objective function $ECO_{\max}$, maximum power output $P_{\max}$, and maximum efficiency $\eta_{\max}$ can be obtained by further numerical computations. Moreover, the power output ($P_{(ECO)}$) at maximum ecological objective function, the power output (P_{η}) at maximum efficiency and the efficiency ($\eta_{(ECO)}$) at maximum ecological objective function, the efficiency (η_p) at maximum power output can be obtained. The characteristic curves of three powers ($P_{\max}$, $P_{(ECO)}$, P_{η}) and three efficiencies ($\eta_{\max}$, $\eta_{(ECO)}$, η_p) are shown in Figures 8 and 9.

Figures 8 and 9 illustrate the influences of E' on powers ($P_{\max}$, $P_{(ECO)}$, P_{η}) and efficiencies ($\eta_{\max}$, $\eta_{(ECO)}$, η_p) characteristics. It can be seen that the powers ($P_{\max}$, $P_{(ECO)}$, P_{η}) and efficiencies ($\eta_{\max}$, $\eta_{(ECO)}$, η_p) increase at first and then decrease as E' increases, the variation tendency is similar to the three-dimensional diagrams shown in Figures 5-7. In Figure 9, when $E' = 14.4k_B = E_0$, the transmission of the electrons with energy E_0 is a reversible process, and the characteristic curve of efficiency versus E' reaches its maximum $\eta_{\max} \approx 0.3349$, resulting in no entropy change of the system. From Figures 8 and 9, by taking a compromise

proposal of power output and efficiency into comprehensive consideration, it can be set $E' / (k_B) = 14.4 \sim 18.3$ to make ESE heat engine work at optimal operation ranges. Moreover, in this range, there exist the relationships when E' is fixed, as follows:

$$P_\eta \leq P_{(ECO)} \leq P_{max} \quad (13)$$

$$\eta_P \leq \eta_{(ECO)} \leq \eta_{max} \quad (14)$$

The performance parameters with $E' / k_B = 15$ are listed in Table 1. It can be observed when the design objective is changed into maximum ecological objective function from maximum power output function, the power output drops by 2.68% from P_{max} to $P_{(ECO)}$ whereas the improvement of relative efficiency is 4.56% from η_P to $\eta_{(ECO)}$; when the design objective is changed into maximum ecological objective function from maximum efficiency function, the efficiency drops by 13.53% from η_{max} to $\eta_{(ECO)}$ whereas the relative power output increases sharply by 229.13% from P_η to $P_{(ECO)}$. The above comparative data reveals that selecting maximum ecological objective function as design point is of more significance on the practical design and operation of ESE heat engines, which proposes a compromise to seek for balanced exergy benefits and losses.

5. Conclusions

Based on finite time thermodynamic theory and numerical calculation method, the ecological performance of an irreversible single resonance energy selective electron (ESE) heat engine is studied. It can be concluded as follows: the heat leakage has no effects on maximum power output, but the maximum ecological objective function and maximum efficiency decrease as heat leakage increases; selecting the parameters boundary energy E' and resonance width ΔE reasonably, the objective functions of ECO , P and η can reach their maxima, respectively. From the

optimization with power output and efficiency, a specific range of boundary energy E' is given as a compromise to make ESE heat engine system work at optimal operation regions. By comparing the performances among different optimization objective functions, the significance of selecting maximum ecological objective function as design point is illustrated specifically: when the design objective is changed into ecological objective function from power output function, the efficiency increases obviously in disfavor of a smaller power output decrease; when the design objective is changed into ecological objective function from efficiency function, the power output increases sharply at the cost of a smaller efficiency decrease.

On the basis of current works, the influences of double energy filters, heat transfer loss and the transmission probability of electrons may be further considered systematically and comprehensively, to make the performance optimization of the ESE heat engine model much more perfect and much better to fit the actual conditions. Furthermore, the ecological criterion can be applied to practical ESE systems such as thermionic refrigerator, thermionic generator, thermoelectric generator and combined thermionic-thermoelectric refrigerator etc., to provide a balanced choice for the selection of working parameters, and ultimately to seek for the best compromise between energy benefits and losses.

Acknowledgements

This paper is supported by The National Science Foundation of P. R. China (Project Nos. 51306206, 51576207). The authors wish to thank the reviewers for their careful, unbiased and constructive suggestions, which led to this revised manuscript.

References

1. Pekola J P, Giazotto F, Saira O-P. Radio-frequency single-electron refrigerator. *Phys Rev Lett* 2007; 98(3): 037201.
2. Segal D. Single mode heat rectifier: Controlling energy flow between electronic conductors. *Phys Rev Lett* 2008; 100(10): 105901.
3. Galperin M, Saito K, Balatsky A V, Nitzan A. Cooling mechanisms in molecular conduction junctions. *Phys Rev B* 2009; 80(11): 115427.
4. Sols F. Aspects of quantum cooling in electron and atom systems. *Physica E* 2010; 42(3): 466-71.
5. Linke H, Humphrey T E, Lindelof P E, Löfgren A, Newbury R, Omling P, et al. Quantum ratchets and quantum heat pumps. *Appl Phys A* 2002; 75(2): 237-46.
6. Linke H, Humphrey T E, Löfgren A, Sushkov A O, Newbury R, Taylor R P, et al. Experimental tunneling ratchets. *Science* 1999; 286(5448): 2314-7.
7. Humphrey T E. Mesoscopic Quantum Ratchets and the Thermodynamics of Energy Selective Electron Heat Engines. Ph. D. Thesis, University of New South Wales, Sydney, Australia, 2003.
8. Andresen B, Salamon P, Berry R S. Thermodynamics in finite time. *Phys Today* 1984; 37(9): 62-70.
9. Chen L G, Sun F R, Chen W Z. Optimization of the specific rate of refrigeration in combined refrigeration cycles. *Energy* 1995; 20(10):1049-53.
10. Bejan A. Entropy generation minimization: The new thermodynamics of finite-size devices and finite-time processes. *J Appl Phys* 1996; 79(3): 1191-218.

11. Salamon P, Nulton J D, Siragusa G, Andresen T R, Limon A. Principles of control thermodynamics. *Energy* 2001, 26(3): 307-19.
12. Chen L G, Sun F R. *Advances in Finite Time Thermodynamics: Analysis and Optimization*. New York: Nova Science Publishers, 2004.
13. Chen L G. *Finite Time Thermodynamic Analysis of Irreversible Processes and Cycles*. Beijing: Higher Education Press, 2005 (in Chinese).
14. Andresen B. Current trends in finite-time thermodynamics. *Angew Chem Int Ed* 2011; 50: 2690-704.
15. Xia S J, Chen L G, Sun F R. Power-optimization of non-ideal energy converters under generalized convective heat transfer law via Hamilton-Jacobi-Bellman theory. *Energy* 2011; 36(1): 633-46.
16. Ge Y L, Chen L G, Sun F R. Progress in finite time thermodynamic studies for internal combustion engine cycles. *Entropy* 2016; 18(4): 139.
17. Chen L G, Xia S J. *Generalized Thermodynamic Dynamic-Optimization for Irreversible Processes*. Beijing: Science Press, 2016 (in Chinese).
18. Chen L G, Xia S J. *Generalized Thermodynamic Dynamic-Optimization for Irreversible Cycles*. Beijing: Science Press, 2016 (in Chinese).
19. Wang C, Chen L G, Xia S J, Sun F R. Maximum production rate optimization for sulphuric acid decomposition process in tubular plug-flow reactor. *Energy* 2016; 99: 152-8.
20. Li J, Chen L G, Ge Y L, Sun F R. Progress in the study on finite time thermodynamic optimization for direct and reverse two-heat-reservoir thermodynamic cycles. *Acta Phys Sin* 2013; 62(13): 130501 (in Chinese).

21. Ahmadi M H, Ahmadi M A, Sadatsakkak S A. Thermodynamic analysis and performance optimization of irreversible Carnot refrigerator by using multi-objective evolutionary algorithms (MOEAs). *Renew Sust Energy Rev* 2015; 51: 1055-70.
22. Ahmadi M H, Ahmadi M A. Thermodynamic analysis and optimization of an irreversible radiative-type heat engine by using non-dominated sorting genetic algorithm. *Int J Am Energy* 2014; 1-6.
23. Sadatsakkak S A, Ahmadi M H, Bayat R, Pourkiaei S M, Feidt M. Optimization density power and thermal efficiency of an endoreversible Braysson cycle by using non-dominated sorting genetic algorithm. *Energy Convers Manage* 2015; 93: 31-9.
24. Ahmadi M H, Ahmadi M A, Shafaei A, Ashouri M, Toghyani S. Thermodynamic analysis and optimization of the Atkinson engine by using NSGA-II. *Int J Low-Carbon Tech* 2015; ctv001.
25. Açıkkalp E, Yamık H. Modeling and optimization of maximum available work for irreversible gas power cycles with temperature dependent specific heat. *J Non-Equilib Thermodyn* 2015; 40: 25-39.
26. Kaushik S C, Kumar S. Finite time thermodynamic analysis of endoreversible Stirling heat engine with regenerative losses. *Energy* 2000; 25(10): 989-1003.
27. Ahmadi M H, Sayyaadi H, Hosseinzadeh H. Optimization of output power and thermal efficiency of solar-dish Stirling engine using finite time thermodynamic analysis. *Heat Transfer-Asian Res* 2015; 44(4): 347-76.
28. Su S H, Liao T J, Chen X H, Su G Z, Chen J C. Hot-carrier solar cells with quantum well and dot energy selective contacts. *IEEE Quantum Elect* 2015; 51(9): 4800208.
29. Açıkkalp E, Caner N. Application of exergetic sustainable index to the quantum irreversible

- Diesel refrigerator cycles for 1D box system. *Eur Phys J Plus* 2015; 130: 73.
30. Dalkırana A, Açıkkalp E, Caner N. Analysis of a quantum irreversible Otto cycle with exergetic sustainable index. *Physica A* 2016; 453: 316-26.
 31. Açıkkalp E, Caner N. Determining of the optimum performance of a nano scale irreversible Dual cycle with quantum gases as working fluid by using different methods. *Physica A* 2015; 433: 247-58.
 32. Açıkkalp E, Caner N. Performance assessment of an irreversible nano Brayton cycle operating with Maxwell-Boltzmann gas. *Eur Phys J Plus* 2015; 130: 93.
 33. Sadatsakkak S A, Ahmadi M H, Ahmadi M A. Optimization performance and thermodynamic analysis of an irreversible nano scale Brayton cycle operating with Maxwell-Boltzmann gas. *Energy Convers Manage* 2015; 101: 592-605.
 34. Ahmadi M H, Ahmadi M A, Pourfayaz F. Performance assessment and optimization of an irreversible nano-scale Stirling engine cycle operating with Maxwell-Boltzmann gas. *Eur Phys J Plus* 2015; 130(9): 1-13.
 35. Ding Z M, Chen L G, Wang W H, Sun F R. Progress in study on finite time thermodynamic performance optimization for three kinds of microscopic energy conversion systems. *Sci Sin Tech* 2015; 45(9): 889-918 (in Chinese).
 36. Ding Z M, Chen L G, Ge Y L, Sun F R. Performance optimization of total momentum filtering double-resonance energy selective electron heat pump. *Physica A* 2016; 447: 49-61.
 37. Meng F K, Chen L G, Sun F R. A numerical model and comparative investigation of a thermoelectric generator with multi-irreversibilities. *Energy* 2011; 36(5): 3513-22.
 38. Meng F K, Chen L G, Sun F R, Yang B. Thermoelectric power generation driven by blast

- furnace slag flushing water. *Energy* 2014; 66: 965-72.
39. Xiong B, Chen L G, Meng F K, Sun F R. Modeling and performance analysis of a two-stage thermoelectric energy harvesting system from blast furnace slag water waste heat. *Energy* 2014; 77: 562-9.
 40. Chen L G, Meng F K, Sun F R. Thermodynamic analyses and optimizations for thermoelectric devices: The state of the arts. *Sci China: Tech Sci* 2016; 59(3):442-55.
 41. Su S H, Guo J C, Su G Z, Chen J C. Performance optimum analysis and load matching of an energy selective electron heat engine. *Energy* 2012; 44(1): 570-5.
 42. Luo X G, He J Z, Li C, Li R W, Liu N. The impact of energy spectrum width in the energy selective electron low-temperature thermionic heat engine at maximum power. *Phys Lett A* 2013; 377: 1566-70.
 43. Ding Z M, Chen L G, Wang W H, Sun F R. Exploring the operation of a microscopic energy selective electron engine. *Physica A* 2015; 431: 94-108.
 44. Yu Y H, Ding Z M, Chen L G, Wang W H, Sun F R. Power and efficiency optimization for an energy selective electron heat engine with double-resonance energy filter. *Energy* 2016; 107: 287-94.
 45. Bejan A. Theory of heat transfer-irreversible power plant. *Int J Heat Mass Transfer* 1988; 31(6): 1211-9.
 46. Bejan A. Theory of heat transfer-irreversible refrigeration plants. *Int J Heat Mass Transfer* 1989; 32(9): 1631-9.
 47. Chen L G, Wu C, Sun F R. Influence of internal heat leak on the power vs. efficiency characteristics of heat engines. *Energy Convers Manage* 1997; 38(14): 1501-7.

48. Chen L G, Sun F R, Wu C. Effect of heat transfer law on the performance of a generalized irreversible Carnot refrigerator. *J Non-Equilib Thermodyn* 2001; 26(3): 291-304.
49. Zhou S B, Chen L G, Sun F R, Wu C. Optimal performance of a generalized irreversible Carnot engine. *Appl Energy* 2005; 81(4): 376-87.
50. Chen L G, Sun F R, Wu C. Optimal configuration of a two-heat-reservoir heat engine with heat leak and finite thermal capacity. *Appl Energy* 2006; 83(2): 71-81.
51. Ding Z M, Chen L G, Sun F R. Performance characteristic of energy selective electron (ESE) heat engine with filter heat conduction. *Int J Energy & Environ* 2011; 2(4): 627-40.
52. Ding Z M, Chen L G, Sun F R. Modeling and performance analysis of energy selective electron (ESE) engine with heat leaks and transmission probability. *Sci China Phys Mech Astron* 2011; 54(11): 1925-36.
53. He J Z, Wang X M, Liang H N. Optimum performance analysis of an energy selective electron refrigerator affected by heat leaks. *Phys Scr* 2009; 80(3): 035701.
54. Ding Z M, Chen L G, Sun F R. Performance characteristic of energy selective electron (ESE) refrigerator with filter heat conduction. *Rev Mex Fis* 2010; 56(2): 125-31.
55. Zhou J L, Ding Z M, Chen L G, Sun F R. Exploring the optimal performances of irreversible single resonance energy selective electron refrigerators. *Eur Phys J Plus* 2016; 131(5):149.
56. Chen L G, Ding Z M, Sun F R. Model of a total momentum filtered energy selective electron heat pump affected by heat leakage and its performance characteristics. *Energy* 2011; 36(7): 4011-8.
57. Ding Z M, Chen L G, Sun F R. Performance analysis of an irreversible energy selective electron (ESE) heat pump with heat leaks. *J Energy Inst* 2012; 85(4): 227-35.

58. Chen L G, Wu C, Blank David, Sun F R. The multi-objective optimum design method for a radial-axial flow turbine with the criteria of optimum twist at the outlet of blade. *Int J Power Energy Syst* 1998; 18(1): 16-20.
59. Ibrahim A, Rahnamayan S, Martin M V, Yilbas B. Multi-objective thermal analysis of a thermoelectric device: Influence of geometric features on device characteristics. *Energy* 2014; 77: 305-17.
60. Long R, Li B D, Liu Z C, Liu W. Multi-objective optimization of a continuous thermally regenerative electrochemical cycle for waste heat recovery. *Energy* 2015; 93: 1022-9.
61. Ahmadi M H, Ahmadi M A, Feidt M. Thermodynamic analysis and evolutionary algorithm based on multi-objective optimization of performance for irreversible four-temperature-level refrigeration. *Mech Ind* 2015; 16(2): 207.
62. Ahmadi M H, Ahmadi M A, Mellit A, Pourfayaz F, Feidt M. Thermodynamic analysis and multi-objective optimization of performance of solar dish Stirling engine by the centrality of entransy and entropy generation. *Int J Elec Power Energy Syst* 2016; 78: 88-95.
63. Chen L G, Feng H J. *Multi-objective Constructal Optimization for Flow and Heat and Mass Transfer Processes*. Beijing: Science Press, 2016.
64. Liu X, Chen L G, Feng H J, Qin X Y, Sun F R. Constructal design of a blast furnace iron-making process based on multi-objective optimization. *Energy* 2016;109: 137-51
65. Angulo-Brown F. An ecological optimization criterion for finite-time heat engines. *J Appl Phys* 1991; 69(11): 7465-9.
66. Yan Z J. Comment on “Ecological optimization criterion for finite-time heat-engines”. *J Appl Phys* 1993; 73(7): 3583.

67. Arias-Herna'ndez L A, Angulo-Brown F. A general property of endoreversible thermal engines. J Appl Phys 1997; 81(7): 2973.
68. Chen L G, Zhou J P, Sun F R, Wu C. Ecological optimization for generalized irreversible Carnot engines. Appl Energy 2004; 77(3): 327-38.
69. Chen L G, Zhu X Q, Sun F R, Wu C. Exergy-based ecological optimization of linear phenomenological heat transfer law irreversible Carnot engines. Appl Energy, 2006; 83(6): 573-82.
70. Chen L G, Wu X H, Xiao Q H, Ge Y L, Sun F R. Local stability of a generalized irreversible Carnot engine working at the maximum ecological objective function. Environ Eng Manage J 2015; 14(10): 2341-51.
71. Chen L G, Zhang W L, Sun F R. Power, efficiency, entropy generation rate and ecological optimization for a class of generalized irreversible universal heat engine cycles. Appl Energy 2007; 84(5): 512-25.
72. Long R, Liu W. Ecological optimization for general heat engines. Physica A 2015; 434: 232-9.
73. Özel G, Açıkkalp E, Fevzi S A, Hasan Y. Novel thermoenvironmental evaluation criteria and comparing them for an actual heat engine. Energy Convers Manage 2015; 106: 1118-23.
74. Açıkkalp E. Methods used for evaluation of actual power generating thermal cycles and comparing them. Int J Elec Power Energy Syst 2015; 69: 85-9.
75. Açıkkalp E. Exergetic sustainability evaluation of irreversible Carnot refrigerator. Physica A 2015; 436: 311-20.
76. Ahmadi M H, Ahmadi M A, Mehrpooya M, Sameti M. Thermo-ecological analysis and optimization performance of an irreversible three-heat-source absorption heat pump. Energy

- Convers Manage 2015; 90: 175-83.
77. Sahraiea H, Mirani M R, Ahmadi M H, Ashouri M. Thermo-economic and thermodynamic analysis and optimization of a two-stage irreversible heat pump. Energy Convers Manage 2015; 99: 81-91.
 78. Sadatsakkak S A, Ahmadi M H, Ahmadi M A. Thermodynamic and thermo-economic analysis and optimization of an irreversible regenerative closed Brayton cycle. Energy Convers Manage 2015; 94: 124-9.
 79. Liu X W, Chen L G, Wu F, Sun F R. Ecological optimization of an irreversible harmonic oscillators Carnot heat engine. Sci China Series G: Phys Mech Astro 2009; 52(12): 1976-88.
 80. Liu X W, Chen L G, Wu F, Sun F R. Ecological optimization of an irreversible quantum Carnot heat engine with spin-1/2 systems. Phys Scr 2010; 81(2): 025003.
 81. Ding Z M, Chen L G, Sun F R. Ecological optimization of energy selective electron (ESE) heat engine. Appl Math Model 2011; 35(1): 276-84.
 82. Ding Z M, Chen L G, Ge Y L, Liu X W, Sun F R. Ecological performance optimization for an irreversible double resonance electron heat engine. J Eng Thermophys 2014; 35(6): 1035-9 (in Chinese).
 83. Datta S. Electronic Transport in Mesoscopic Systems. Cambridge: Cambridge University Press, 1995.

Table Lists

Table 1. Performance parameters with $E' = 15k_B$

Figure Captions

Figure 1 Irreversible single resonance ESE heat engine model

Figure 2 Influence of heat leakage on ecological objective function versus power output characteristic

Figure 3 Influence of heat leakage on ecological objective function versus efficiency characteristic

Figure 4 Influence of heat leakage on power output versus efficiency characteristic

Figure 5 Three dimensional diagram of ecological objective function ECO versus ΔE and E' characteristic

Figure 6 Three dimensional diagram of power output versus ΔE and E' characteristic

Figure 7 Three dimensional diagram of efficiency versus ΔE and E' characteristic

Figure 8 Power output characteristics with different objective functions

Figure 9 Efficiency characteristics with different objective functions

Table 1. Performance parameters with $E' = 15k_B$

<i>Power output ($P / (W)$)</i>	<i>Value</i>	<i>Efficiency (η)</i>	<i>Value</i>
$P_{\max}$	1.229×10^{-13}	$\eta_{\max}$	0.3208
$P_{(ECO)}$	1.196×10^{-13}	$\eta_{(ECO)}$	0.2774
P_{η}	3.330×10^{-14}	η_P	0.2653

Figure 1. Irreversible single resonance ESE heat engine model

Figure 2. Influence of heat leakage on ecological objective function

versus power output characteristic

Figure 3. Influence of heat leakage on ecological objective function
versus efficiency characteristic

Figure 4. Influence of heat leakage on power output versus efficiency characteristic

Figure 5. Three dimensional diagram of ecological objective function ECO
versus ΔE and E' characteristic

Figure 6. Three dimensional diagram of power output P
versus ΔE and E' characteristic

Figure 7. Three dimensional diagram of efficiency η versus ΔE and E' characteristic

Figure 8. Power output characteristics with different objective functions

Figure 9. Efficiency characteristics with different objective functions