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

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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%.

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

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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-Hernandez 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 systems, 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

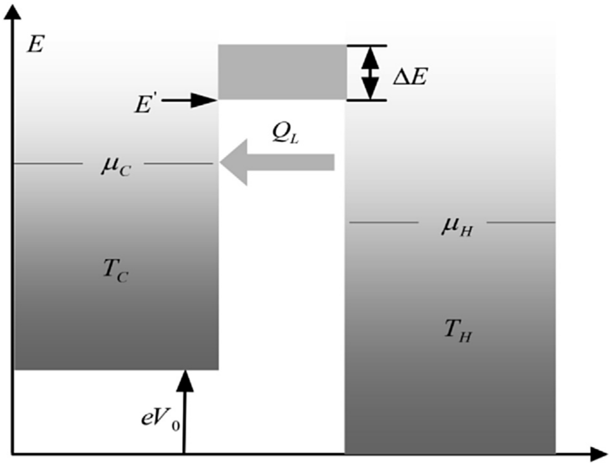

Fig. 1. Irreversible single resonance ESE heat engine model.