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Power and efficiency optimization for an energy selective electron heat engine with double-resonance energy filter

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ABSTRACT

Theoretical modeling for a microscopic ESE (energy selective electron) heat engine with double-resonance energy filters is performed in this paper. The heat flow characteristics and performance parameters are discussed in two different cases according to the positions for central energy level of double resonances. It is found that the analytical expressions for performance parameter such as power output or efficiency in the two cases share the identical form. The optimal performance for the ESE heat engine system is analyzed by using finite time thermodynamic theory. The performance curves and fundamental optimal relation for the system's output power and efficiency are explored with numerical examples. The fundamental optimal relation of power and efficiency is an open loop-shaped curve. There exist a maximum efficiency and a maximum power output. The optimal operating regions of the power and efficiency are determined and the influences of the system's design parameters are discussed. Finally, a comparison of the ESE engine system with double- and single-resonance filters is carried out in order to show the performance differences and the effect of the newly adopted double resonances. The utilization of double-resonance energy filter leads to increased power output while decreased efficiency for the electron heat engine device.

1. Introduction

In addition to large-scale devices, another important direction in developing energy conversion systems is miniaturization. The development of very small power generation or refrigeration devices offers the potential of reliable and highly efficient energy conversion in microscopic scale. These devices would reveal a wide array of new applications such as cryogenic refrigeration, heat dissipation in integrated circuits, and so on. The typical miniature system includes quantum-dot heat engines, single electron refrigerators, thermionic refrigeration devices and etc. Recently, the ideas of refrigeration or power generation based on mesoscopic electron transport have attracted considerable attentions. Much effort has been paid to explore the energy conversion mechanisms of these electronic systems. The theoretical model of ESE (energy selective electron) engine was firstly proposed as a quantum Brownian heat engine in reversible condition by using mesoscopic semiconductor ratchet. Electrons are served as the working medium of the Brownian motor. The distinctive feature of ESE engine is the energy selectivity for electrons according to their energy levels which is realized by an energy filter [1,2]. By means of the energy filter, the maximum efficiency for the ESE system can achieve Carnot value. The rapid development of the nanotechnology has turned the electron filtering process into reality. Many new nanostructures or devices such as quantum dots, nanowires, quantum wells and so on can be functioned as energy filter in practical electron devices [3–6].

So far, much research work has been done to explore to the mechanism and efficiency of energy conversion for ESE system. The obtained results for theoretical ESE models have already been used as guidelines for improving the performance of practical energy systems, such as nanowire based thermoelectric devices [7–10], semiconductor solid-state thermionic and thermoelectric devices

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Nomenclature

dE	energy range for electrons (J)
E	energy level (J)
eV_0	applied bias voltage
f	Fermi-Dirac distribution
Δf	difference of Fermi distribution of two reservoirs
h	Plank constant
k_B	Boltzmann's constant
$\dot{N}$	net electron flow
P	power output (W)
$\dot{Q}$	heat flow rate (W)
T	temperature for electron reservoir (K)
ΔE	energy spacing (J)
δE	resonance width (J)

Greek symbols

η	efficiency for the system
ε	chemical potential for electron reservoir (J)

Subscripts

C	cold reservoir
H	hot reservoir
max	maximum value
min	minimum value
0	reversible condition
1	the first resonance of energy filter
2	the second resonance of energy filter
+	increased heat flow rate
−	lost heat flow rate

[11–13], vacuum thermionic generators and refrigerators [14,15], and hot carrier solar cells [16,17].

There exist two central topics as to the studies for ESE engine systems. One is the thermodynamic performance analysis which reveals internal working mechanism and the performance limits of ESE system, and provides the instructions for the optimal operation for practical systems. In doing so, the theory of FTT (finite time thermodynamics) [18–42], which has achieved extensive application in conventional macroscopic energy conversion systems [43–53] and recently extended to microscopic systems (such as molecular motors [54,55], Brownian motors [56–61], quantum dot ratchets [62–65], and nano-scale engine cycles [66–68]), has been applied and a series of meaningful results have been drawn. Performance characteristics of electronic engine system working respectively as heat engine [69–75], refrigerator [69,76–79] and heat pump [80,81] have been analyzed and optimized; and the optimal performance parameters and operation regions have been explored and determined. In the analyses, various performance criteria such as conventional output rate (including power output, cooling load and heating load), energy conversion efficiency, efficiency at maximum power (COP which is defined as the ratio of cooling load to power input at maximum figure of merit), ecological function and so on have been adopted for performance optimization.

The other central topic is the improvement of ESE engine models which makes the theoretical models be closer to practical micro energy conversion systems and provides the instructions for optimal design and operation of practical ESE systems. It is found that the heat leakage caused by the phonon transmission in filter structure between electron reservoirs is an essential part for establishing a comprehensive ESE engine model [71,76]. Recently, irreversible models of ESE engine systems have been established and the influences of heat leakage have been discussed [72,77,81]. The electron filtering pattern and the transmission probability function are two properties characterizing the electron transportation process. Efforts have also been devoted to identify the influences of electron filtering mechanism [69,82,83] and transmission probability function [73,80,81,84], and to reveal their relations with the thermodynamic performance characteristics of ESE engines.

Besides the influences of transmission probability function, filtering pattern and heat leakage, another important consideration for ESE engine is the structure of energy filter. In some analyses, the energy filter between the electron reservoirs contains only one tunneling resonance. Actually, energy filter with double or multiple resonances can also be implemented for the ESE engines, exemplified by the recently proposed double-resonance ESE refrigerator [85,86] and heat pump [87]. The energy filter of the ESE refrigerator contains two separate resonances for electrons, which is similar to the practical double dot quantum ratchet [88] as well as the solid-state thermionic refrigerators with multiple barriers [89,90]. In order to show more clearly the performance and energy conversion mechanism of ESE engine, it is of great theoretical significance to analyze the performance of the ESE system operating respectively as refrigerator, heat pump or heat engine.

Based on Refs. [1,85,86], this paper tries to establish a theoretical model of ESE heat engine with double resonances and analyze its optimal performance with FTT theory. The major purpose is to reveal the influence of double resonance filters on the optimal performance of electron system operating as a heat engine and to explorer further the operation of microscopic electron engine system. The model established in the present paper is different from previous models in several aspects: Firstly, the conventional electron filtering pattern of the present model is different from the total momentum electron filtering mode in Ref. [83]. Secondly, the heat engine operating mode is different from the refrigerator or heat pump mode in Refs. [85,86]. Moreover, the present paper analyzes the fundamental optimal relation for power and efficiency while in Ref. [75] the ecological performance is studied. By analyzing the heat flows in two different cases, the analytical expressions of performance parameters for ESE heat engine system will be obtained. The fundamental optimal relation for power and efficiency as well as the influences of resonance width and the energy spacing on performance characteristics of the system will be investigated by using numerical examples. The effect of newly added double-resonance energy filter will be discussed by performance comparison for the devices with different kinds of filters. The obtained results are of theoretical significance for designing practical electron-based devices with multi-resonances such as thermionic power generation and refrigeration devices.

2. Modeling details for double-resonance ESE heat engine

As shown in Fig. 1, a heat engine model contains two electron reservoirs and an energy filter with double resonances which transmit/block electrons within specified energy ranges. The two reservoirs are set with different chemical potentials (ε_C and ε_H) and temperatures (T_C and T_H). For the energy filter, the two resonances are located in different energy positions with the central energy levels E_1 and E_2. The two resonances are supposed to be of the same width δE and the energy spacing between them is ΔE. The electron transportation process and performance characteristic of the