Physica A 447 (2016) 49–61

Contents lists available at ScienceDirect

Physica A

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

Performance optimization of total momentum filtering double-resonance energy selective electron heat pump

Ze-Min Ding, Lin-Gen Chen*, Yan-Lin Ge, Feng-Rui Sun

Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, PR China
Military Key Laboratory for Naval Ship Power Engineering, Naval University of Engineering, Wuhan 430033, PR China
College of Power Engineering, Naval University of Engineering, Wuhan 430033, PR China

HIGHLIGHTS

- A model for energy selective electron (ESE) heat pumps is establishedwith two-dimensional electron reservoirs and a double-resonance energy filter.
- A total momentum filtering mechanism is considered for the transmission of electrons.
- The optimal thermodynamic performance of ESE heat pump devices is investigated.

ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form 7 October 2015
Available online 21 November 2015

Keywords:
Energy selective electron heat pump
Double resonance
Total momentum filtering mode
Optimal performance
Finite-time thermodynamics

ABSTRACT

A theoretical model for energy selective electron (ESE) heat pumps operating with two-dimensional electron reservoirs is established in this study. In this model, a double-resonance energy filter operating with a total momentum filtering mechanism is considered for the transmission of electrons. The optimal thermodynamic performance of the ESE heat pump devices is also investigated. Numerical calculations show that the heating load of the device with two resonances is larger, whereas the coefficient of performance (COP) is lower than the ESE heat pump when considering a single-resonance filter. The performance characteristics of the ESE heat pumps in the total momentum filtering condition are generally superior to those with a conventional filtering mechanism. In particular, the performance characteristics of the ESE heat pumps considering a conventional filtering mechanism are vastly different from those of a device with total momentum filtering, which is induced by extra electron momentum in addition to the horizontal direction. Parameters such as resonance width and energy spacing are found to be associated with the performance of the electron system.

1. Introduction

Recently, research on microscopic engine systems, where the electrons serve as the working substance, has attracted much attention because of its theoretical importance for the construction of miniature energy conversion devices. The so-called energy selective electron (ESE) engine was initially referred to as a mesoscopic semiconductor ratchet in a one-dimensional system [1]. One important property of the ESE system is that it can control the transmission of electrons between electron reservoirs by means of a special energy filter [2]. Theoretically, the ESE engine can achieve the Carnot

---

* Corresponding author at: Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, PR China. Tel.: +86 27 83615046; fax: +86 27 83638709.

E-mail addresses: lgchenna@yahoo.com, lingenchen@hotmail.com (L.-G. Chen).

http://dx.doi.org/10.1016/j.physa.2015.11.017

Nomenclatures

E	energy level of an electron (J)
e	charge of an electron (C)
f	Fermi–Dirac distribution
$\hbar$	reduced Plank constant ($\text{J} \cdot \text{s}$)
k_B	Boltzmann constant (J/K)
k_r	total momentum filtering mode
k_x	conventional filtering mode
m^*	effective mass (kg)
$\dot{G}$	electron flux
$\dot{Q}$	rate of heat transfer (W)
T	temperature (K)
V_0	bias voltage (V)
w	width parameter (J^{-2})

Greek symbols

β	COP
ΔE	resonance width (J)
δE	energy spacing (J)
ε	chemical potential (J)
ξ	transmission probability
π	heating load (W)

Superscripts

max	maximum value
$+, -$	increased (+) and lost (-) amounts of heat

Subscripts

C	cold electron reservoir
d	device with double resonance
H	hot electron reservoir
r	k_r-filtering device
s	device with single resonance
x	k_x-filtering device
0	reversible operation
1, 2	the first/second resonance

efficiency by precisely controlling the electron transmission process through the energy filter. This system has excellent performance characteristics, leading to several studies on its practical application and theoretical optimization.

The thermionic and thermoelectric energy conversion systems are typical examples for practical ESE engine systems with filtering functions. In vacuum or solid-state thermionic devices, the internal electron transmission process between two electrodes is constrained by the work functions or the wide-bandgap heterostructure material of the emitters. To date, the results of theoretical research on the ESE systems have been used to analyze and improve the performance of the actual thermionic devices. It has been shown that the performance of vacuum thermionic devices [3,4] and nanowire thermoelectric devices [5–7] can be further improved because of the improved electron transmission by optimizing the energy spectrum of transmitted electrons. Similar results can also be found for their applications in quantum-dot heat engines.

Optimization of thermodynamic performance is one of the most important aspects of the theoretical analysis of ESE engine systems. The finite-time thermodynamic (FTT) theory is an effective tool to reveal the essential mechanism and efficiency of energy conversion systems [8–35]. Recently, the theory has been widely used in the performance optimization of ESE engine systems. For theoretical optimization, an electron engine model with a single-resonance energy filter would be a major topic of research [2,36–39]. Under different transmission conditions, the single-resonance electron system can serve as a heat engine [2,36,37,39], refrigerator [2,38,39], or heat pump [39,40], similarly to the conventional macroscopic energy conversion systems [41–44]. The ESE engine model with single resonance was then improved by considering the different transmission patterns, as well as the irreversible heat leakage caused by the transmission of phonons between two electron reservoirs [39,45–49]. Both the transmission probability functions and irreversible heat leakage have quantitative and qualitative effects on the performance of the irreversible ESE engines [39,50–52]. In addition to the basic output rate