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Optimum performance analysis of a combined thermionic-thermoelectric refrigerator with external heat transfer

Z.M. Ding [a, b, c], L.G. Chen [a, b, c, *], F.R. Sun [a, b, c]

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

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A B S T R A C T

An irreversible combined thermionic-thermoelectric refrigerator model with external finite rate heat transfer is established. The general expressions for cooling load and coefficient of performance (COP) versus applied voltage are derived. The performance of the irreversible combined refrigerator, in which the heat transfer between the device and the heat reservoir obeys Newton's heat transfer law, is analyzed and optimized by using the combination of finite time thermodynamics and non-equilibrium thermodynamics. The influence of external heat transfer is investigated by comparing the performance of irreversible combined refrigerator with the traditional analysis without heat transfer losses. The performances of the combined refrigerator device with external heat transfer are further compared with those of an independent vacuum thermionic refrigerator with and without considering external heat transfer, respectively. Moreover, for the fixed total heat transfer surface area of four heat exchangers, the allocations of the heat transfer surface area among the four heat exchangers are optimized for maximizing the cooling load and the COP. The effect of total heat transfer surface area on the optimum performance of the irreversible refrigerator is explored by numerical examples. The results obtained herein may provide guidelines for the design and application of practical combined thermionic-thermoelectric refrigeration devices.

1. Introduction

The performance of thermionic energy conversion systems has been analyzed for many years [1–4]. Usually, practical thermionic power generators are operating at high temperatures. The idea of thermionic refrigeration was first presented by Mahan [5] as a vacuum diode. Some researchers have been carried out on vacuum thermionic devices [6,7]. However, due to the space charge effect and the lack of stable electrode materials with sufficiently low work function, practical vacuum thermionic refrigeration can hardly find application at room temperatures.

Recent researches on nanometer gap vacuum device have brought new expectations for room temperature application of vacuum thermionic refrigeration. Hishinuma et al. [6] had shown that the use of nanometer gap between the emitter and the collector via quantum tunneling could lower the work function and high enough emission current for room temperature application could be achieved. They further proposed that using a semiconductor heterojunction–vacuum interface in thermionic emission to further reduce the height of the vacuum potential and achieved higher still current [8,9]. Gerstenmaier and Wachutka [10,11] had performed detailed analyses of the performance of nanometer gap thermionic device and got the similar results. Moreover, O'Dwyer et al. [12] analyzed the performance of thermionic refrigerator with emitter-collector separations in the order of a few nanometers and examined the effect that the nature of the spectrum of electrons transmitted between the electrodes had on the thermionic refrigerator performance.

In order to overcome the limitations of vacuum thermionic refrigeration at lower temperature application, Shakouri and Bowers [13] proposed that using semiconductor heterostructures to achieve thermionic cooling. A serious problem in semiconductor device is the

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[*] Corresponding author. Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, PR China.
E-mail address: lgchenna@yahoo.com (L.G. Chen).

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List of symbols

A_0	Richardson's constant, A m^{-2} K^{-2}
F	heat transfer surface area, m^2
f	allocation of heat transfer surface area
F_0	inner surface area of the electrodes, m^2
J	emitted current, A
K	thermal conductance, W K^{-1}
k	heat transfer coefficient, W m^{-2} K^{-1}
k_B	Boltzmann's constant, J K^{-1}
n	number of thermoelectric refrigerating elements
P	power input, W
Q	rate of heat flow, W
$\dot{Q}$	rate of heat flow per unit area, W m^{-2}
q	charge of an electron, C
R	cooling load,/electrical resistance, Ω
T	temperature, K
V	applied voltage, V

Greek letters

α	Seebeck coefficient, V K^{-1}
ε	coefficient of performance for refrigerator (COP)
ϕ	work function, eV
μ	thermal emissivity of the electrode surfaces
σ	Stefan–Boltzmann constant, W m^{-2} K^{-4}

Subscripts

a	total heat transfer surface area of the thermionic refrigerator
b	total heat transfer surface area of the thermoelectric refrigerator
C	cold heat reservoir
e	electrical resistance
H	hot heat reservoir
i	corresponding value without considering external heat transfer
max	maximum value
N	N-type thermoelectric element
P	P-type thermoelectric element/passive conductor
R	radiation heat losses
T	total heat transfer surface area
TE	thermoelectric refrigerator
TI	thermionic refrigerator
1,2	anode and cathode for thermionic refrigerator
3,4	hot and cold junctions for thermoelectric refrigerator

inherent heat conduction of the semiconductor material, which doesn't exist in the vacuum devices. This heat conduction has great influence on the performance of the vacuum devices. Later, Mahan and Woods [14] suggested that using multi barrier structure to achieve cooling, in which the overall heat conduction of the entire barrier can be greatly reduced. Ever since then, many efforts have been devoted to the study of single and multi-barrier thermionic cooling devices, theoretically [15–20] and experimentally [21–23].

Essentially, the energy conversions in both thermionic and thermoelectric devices are induced by the transport of electrons. In thermionic devices, the transport of electron is ballistic while in thermoelectric devices, the transport of electron is diffusive. Considering the similarities of the two kinds of devices, some researchers compared the performances of thermoelectric and thermionic refrigeration systems. Nolas and Goldsmid [24] compared vacuum thermionic refrigerators with thermoelectric refrigerators under idealized conditions, and showed that the performance of the thermionic device was generally superior to that of the thermoelectric refrigerator. However, the materials needed for the devices studied in their work are not yet available at present. Ulrich et al. [25] compared solid-state thermionic refrigeration with standard thermoelectric refrigeration and found that the performance of both thermionic and thermoelectric refrigerators relies on the same material parameters. They found that for all known materials, single barrier thermionic refrigeration was less effective and less efficient than thermoelectric refrigeration.

As to the vacuum thermionic device model considered in Nolas and Goldsmid's work [24], a passive conductor, which was an essential part of a return path for the electrical current in the device, was taken into account. Besides radiation losses of the thermionic electrodes, the passive conductor would cause additional losses due to Joule heating and heat conduction. Based on this refrigerator model with passive conductor, Xuan [26] further presented a novel combined thermionic-thermoelectric refrigerator by replacing the passive metal conductor in an independent thermionic refrigerator with an active P-type thermoelectric element. It was shown that due to the Peltier cooling power of the thermoelectric element, the combined thermionic-thermoelectric refrigerator is more effective and efficient than independent thermionic or thermoelectric refrigeration device.

However, in Xuan's work, the analyses were mainly based on non-equilibrium thermodynamics in which the refrigerator was assumed to be thermally insulated from surroundings and the finite rate heat transfer between the refrigerator and the heat reservoirs was ignored. In fact, the external heat transfer between the electrode and external heat reservoir is inherently irreversible. Results of some analyses indicate that the thermal resistances between the heat reservoir and the hot or cold side of the device have significant influences on the performances of thermionic refrigerators [27] or thermoelectric refrigerators [28] alone. Thus, in the analysis of such a combined thermionic-thermoelectric refrigerator, the external finite rate heat transfer between the device and the heat reservoirs is not negligible in order for more practical and accurate results.

The theory of finite time thermodynamics (FTT) [29–36] is a powerful tool for performance analysis and optimization of practical thermodynamic processes and devices. The irreversibility of finite rate heat transfer, which is not considered in the conventional non-equilibrium thermodynamic analysis, is one of the most important facts concerning finite time thermodynamics. Much research work has been carried out on performance analysis and optimization for conventional thermodynamic processes and devices [37–39], thermoelectric energy conversion systems [40–42] and thermionic energy conversion systems [43–47] by using the theory of FTT, in which the effects of finite rate heat transfer between the device and the external reservoir are taken into account in detail.

However, at present, there has been no investigation concerning the FTT performance for the combined thermionic-thermoelectric refrigerator published in the open literature. Thus, on the basis of the exoreversible model of combined thermionic-thermoelectric refrigerator presented in Ref. [26], an irreversible combined thermionic-thermoelectric refrigerator model with external finite rate heat transfer is established in this paper. The general formula for cooling load and COP of the combined thermionic-thermoelectric refrigerator are derived by assuming that the heat transfer between the device and the heat reservoir obeys Newton's heat transfer law. The optimal performance of the combined device is obtained and the effect of the heat source temperature is analyzed by numerical examples. The