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Performance analysis of a thermosize micro/nano heat engine

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Abstract

In a recent paper [A. Sisman, I. Muller, Phys. Lett. A 320 (2004) 360] the thermodynamic properties of ideal gases confined in a narrow box were examined theoretically. The so-called "thermosize effects" similar to thermoelectric effects, such as Seebeck-like thermosize effect, Peltier-like thermosize effect and Thomson-like thermosize effect, were analyzed. Like the thermoelectric generator, based on the thermosize effects we have established a model of micro/nano scaled ideal gas heat engine cycle which includes two isothermal and two isobaric processes. The expressions of power output and efficiency of this cycle in the two cases of reversible and irreversible heat exchange are derived and the optimal performance characteristics of the heat engine is discussed by some numerical example. The results obtained here will provide theoretical guidance for the design of micro/nano scaled device.

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Keywords: Thermosize effects; Thermoelectric effects; Thermodynamic cycle; Performance characteristics

1. Introduction

In micro/nano mechanical systems, the mean thermal wave length of gas atoms may be comparable with the size of the system, and the Casimir-like size effect becomes important one. In recent years, the boundary effect on the ideal classical gases confined in a rectangular box or spherical and cylindrical geometries is studied theoretically in [1,2]. The dependence of the boundary effect on ideal quantum gases is analyzed in [3–5]. In general, the expressions of the thermodynamic quantities of the ideal gases in micro/nano mechanical systems are the appropriate conventional terms plus correction terms. These global thermodynamic quantities are non-additive and depend strong on the size of the box or containers. When atoms pass from one box to another one of different size through a permeable wall, the size difference creates "thermosize effects" similar to thermoelectric effects [1].

With the rapid development of the nanotechnology it makes us possibly to design the micro/nano scaled devices [6–8]. Therefore, it is necessary to study further the thermosize effects (Seebeck-like thermosize effect, Peltier-like thermosize effect and Thomson-like thermosize effect) and design a micro/nano scaled ideal gas device based on these effects. In this Letter, similar to the thermoelectric generator [9–12], we establish the thermodynamic cycle model of a thermosize micro/nano heat engine in which is composed of two isothermal and two isobaric processes. The power output and efficiency of the heat engine are calculated in the two cases of reversible and irreversible heat exchange. Furthermore, the influence of Fourier's heat flow on the performance of the cycle is analyzed. Some performance characteristic curves are plotted by numerical example and the results obtained here will provide theoretical guidance for the design of micro/nano scaled device.

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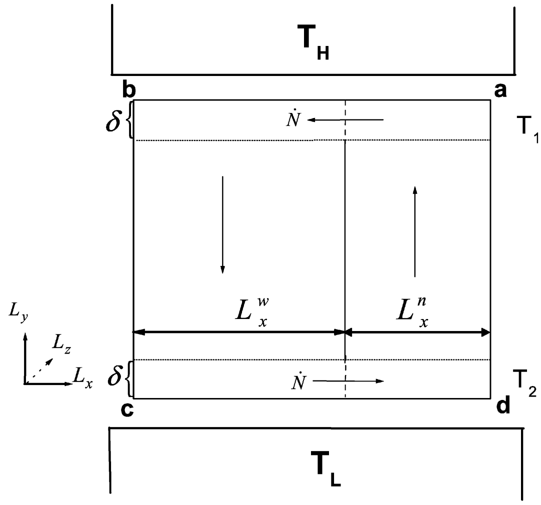

Fig. 1. Schematic diagram of a thermosize micro/nano heat engine.

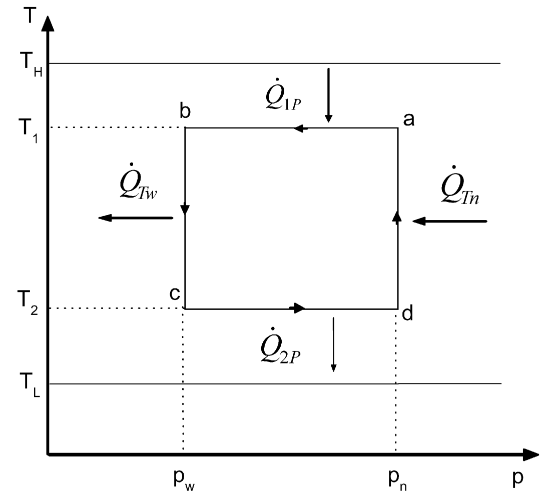

Fig. 2. The T–p diagram of a thermosize micro/nano heat engine.

2. A micro/nano scaled heat engine model

Consider a rectangular box with the micro/nano dimensions of L_x, L_y and L_z. The box is divided into two different scale portions by an adiabatic wall, respectively, called narrow (L_x^n) and wide (L_x^w). The walls located in the bottom and top of the boxes are permeable for the atoms of the gas and the width of permeable walls is δ. The ideal gases are filled in this box. In particular, the permeable wall is a wall, which contains many small holes without disturbing the stationary de Broglie wave patterns in each box. Schematic diagram of a micro/nano scaled ideal gas heat engine is shown in Figs. 1–2, which is composed of the two isothermal and two isobaric processes. This cycle is a microscopic analog of the Ericsson heat engine cycle. T_H and T_L are the temperatures of the hot reservoir and the cold reservoir, respectively. T_1 and T_2 are the temperatures of the gas fluid in two isothermal processes, respectively. And there is a relation, $T_H > T_1 > T_2 > T_L$. In the two isobaric processes, a regenerator is often used to improve the performance of the heat engine cycle.

According to the Seebeck-like thermosize effect in micro/nano mechanical system [1], when the upper permeable wall is close but the lower permeable wall is open, the boxes can exchange atoms through the lower permeable wall. Then the top of the narrow and wide boxes have different chemical potential. Because of the different chemical potentials, there is a "potential for a gas fluid" across the wall and a gas fluid would occur. This chemical potential difference is called "thermosize potential" and the expression is given by

$$V_{\text{th-size}} = \int_{T_2}^{T_1} \frac{k_b}{\sqrt{\pi}} \left(\frac{1}{L_x^n} - \frac{1}{L_x^w}\right) \left[L_c(T_2) - \frac{L_c(T)}{2}\right] dT, \tag{1}$$

where $L_c(T) = h/\sqrt{8mk_bT}$ is one half of the most probable de Broglie wave length of the particles at temperature T, h is Planck's constant, m is the atomic mass and k_b is Boltzmann's constant. Furthermore, when the upper and the lower permeable wall are open, a gas fluid would occur continuously. The mechanical system may be regarded as a micro/nano scaled ideal gas heat engine based on the thermosize effects. It is the analogues of thermoelectric generator based on thermoelectric effect [9–12].

Now assume that a steady gas fluid $\dot{N}$ passes through the narrow and wide rectangular boxes. When the gas fluid passes through the upper permeable wall from state a to state b and maintains the constant temperature T_1, the gas flow will absorb heat quantity from the hot reservoir,

$$\dot{Q}_{1P} = \dot{N} T_1 \frac{k_b L_c(T_1)}{2\sqrt{\pi}} \left(\frac{1}{L_x^n} - \frac{1}{L_x^w}\right), \tag{2}$$

which is called as Peltier-like thermosize effect. Similarly, when the gas fluid passes through the lower permeable wall from state c to state d and maintains the constant temperature T_2, the gas fluid will reject heat quantity to the cold reservoir,

$$\dot{Q}_{2P} = \dot{N} T_2 \frac{k_b L_c(T_2)}{2\sqrt{\pi}} \left(\frac{1}{L_x^n} - \frac{1}{L_x^w}\right). \tag{3}$$