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Rotating thermoelectric device in periodic steady state

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ABSTRACT

We propose a novel rotating thermoelectric device operating in periodic steady state, whether it is possible to achieve better energy conversion performance for rotating device comparing to conventional stationary steady state. The rotating thermoelectric (TE) cooling device consisting of the single TE conductor is described. It operates in two periodical steady state modes: the switching periodical mode (P-mode) when hot and cold ends of the TE conductor are periodically instantly reversed and the continuous sinusoidal mode (S-mode) when the temperature of TE conductor edges varies continuously according to a sine wave. Cooling and power generation regimes of rotating (TE) device in the periodic steady state was studied analytically. The efficiency and the cooling temperature of rotating TE device was found to depend not only on the dimensionless TE figure of merit, but also upon an additional dimensionless parameter comprising of the rotation period, the size and the thermal diffusivity of the TE conductor. The proposed analytical method can be generalized to even more complex rotating cooling modes and allows us to solve the optimization problem for cooling TE device parameters. The S-mode was shown to demonstrate deeper cooling at certain times.

1. Introduction

The main way to improve the efficiency of thermoelectric (TE) devices – power generators, coolers, etc. is to increase the dimensionless figure of merit of TE materials – $ZT = \alpha^2\sigma T/\kappa$, where α – the Seebeck coefficient, σ – the electrical conductivity, T – the absolute temperature, κ – the thermal conductivity.

Unlike of the superconductivity, where new materials with high transition temperatures to the superconducting state have been invented, the progress in ZT improvement of TE materials is quite disappointing. Thus, for example, at room temperature ($T = 300$ °K) from 1950 to the present time the figure of merit rose from $ZT \sim 1$ to $ZT \sim 1.2 \div 1.3$ only [1–5]. Moreover, today there is no commercially available TE materials with $ZT \sim 1.3$. Indeed, for common appliances use, for example, in the household or industrial refrigeration, TE materials with the figure of merit $ZT \geqslant 2.0$ [6–8] are required. There were expectations that the success can be achieved using tunneling and other quantum effects in nanostructured TE materials [5,9–13]. However, there is no significant progress so far.

Also, the constant interest to the problem of thermoelectric power generation and cooling method produce a new design features for the TE devices, such as the shape variations [14], additional attachments that increase the efficiency of TE devices [15,16] etc.

The parameters of TE device in the stationary steady state depend only on the figure of merit ZT [17]. The higher ZT, the lower cooling temperature can be reached.

In transient modes, the efficiency of TE device is affected by many other parameters such as the temperature diffusivity, the current pulse duration in a pulsed mode [6,18–22], the relaxation time of thermal processes etc. Such transient modes are constantly attract the attention of researchers [5,18–31] because such modes have advantages over the stationary steady state. For example, at certain times in a pulsed cooling mode [18–22] deeper cooling can be reached. Optimization of transient mode parameters allows to improve the operation of TE device as compared with the stationary steady state even the same TE materials are used.

Qualitatively, the improved performance of TE devices in the transient mode is possible due to the fact that the relaxation time of electrical processes is negligible compared to the relaxation time of thermal processes [17]. When the current flows through TE device in the cooling regime in the stationary steady state, the Peltier heat removed from the cold junction and the Joule heat

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Nomenclature

TE	abbreviation for "thermoelectric"
α	Seebeck coefficient
σ	electrical conductivity
ρ	specific resistivity $1/\sigma$
κ	thermal conductivity
ZT	dimensionless figure of merit
t	time
x	coordinate along the TE conductor
$T(x,t)$	temperature of the TE conductor
$j, j(t)$	current density in the TE conductor
c_v	specific heat
ρ_0	bulk density
χ	thermal diffusivity: $\chi = \kappa/c_v\rho_0$
P-mode	the switching periodical mode
S-mode	the continuous sinusoidal mode
T_C, T_H	absolute temperatures of cold and hot ends (junctions) of the TE conductor
$\bar{T}$	mean temperature: $(T_C + T_H)/2$
T_0	amplitude of temperature variation $(T_H - T_C)/2$
ΔT	temperature difference: $T_H - T_C = 2T_0$
S	cross section of TE conductor
$l = 2a$	length of the TE conductor
P	rotation period
ω	cycling frequency $\omega = 2\pi/P$
Q_C, Q_H	heat flux at cold and hot ends of the TE conductor
η	power generation efficiency

generated in the TE conductor are balanced. Increased current and, consequently, increased Joule heat would make the TE device inoperative. In the transient state, due to the relaxation times difference, the heat balance is uncompensated. Higher current passed through the TE device for a short time delivers additional cooling. The optimization of the length and the shape of current pulses can give deeper cooling on limited time intervals [20] or the cooling of small objects in a shorter time [21].

The pulsed cooling [23–26] consists of two major phases. The first phase is highly transient one implementing fast and deep cooling, the second phase is the relaxation, in this phase, as a rule, the TE device is out of use.

This paper studies TE devices operating in the periodic steady state mode. Unlike the pulsed cooling, the TE device in the periodic steady state mode operates continuously. The basic question considered here, whether it is possible in this periodic steady state mode to achieve better performance relative to the stationary steady state mode, at least better at certain times. In this study, we omit particular technical details such as the contact resistance of the plates, the lateral heat transfer, parameters of the cooled object etc.

The proposed TE devices consist of a single TE conductor with the constant cross section made of thermoelectric material and the role of second conductor plays body of the TE device, which is an ordinary metal conductor.

We consider two types of periodic steady state modes for proposed TE devices: the switching periodical mode (P-mode) when hot and cold ends of TE conductor are periodically instantly reversed and the continuous sinusoidal mode (S-mode) when temperature of TE conductor edges varies continuously according to a sine wave.

For periodic steady state modes, along with ZT we found a new dimensionless parameter that is the combination of the period of temperature change, the TE conductor size and its temperature diffusivity. The optimal value of above parameter was calculated.

In the next section TE devices in P- and S-modes are schematically described. Following sections contain analytical calculations and results for P-mode in the power generation and cooling regimes, and for the S-mode cooling regime. The last section presents discussion and conclusions.

2. Model of the device in a periodical steady state

The TE device operating in the switching periodical mode (P-mode) is shown schematically in Fig. 1a. The TE conductor turns periodically in the plane of the figure and its hot and cold ends (junctions) are instantly swapped.

The TE device operating in the continuous sinusoidal mode (S-mode) is presented schematically in Fig. 1b. Let the TE conductor rotates in the hole of the orifice plate with linear temperature distribution from up to down (see Fig. 1b), consequently at the ends (junctions) of the rotating TE conductor (see Fig. 1b) the temperature varies continuously by the sine wave.

The TE device (Fig. 1a and b) consists of a single TE conductor with the constant cross section S of the length $l = 2a$. Other parts of TE device do not have TE properties. The period of rotation P is fixed.

Performing further analytical calculations for both P- and S-modes we assume for convenience that the TE conductor is fixed in plane but the temperature at its ends (junctions) varies according to the periodic law specific for each mode.

The heat conduction equation for the TE conductor in TE devices has the standard form [17]

$$c_v\rho_0\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial x^2} + \rho j^2, \tag{1}$$

where t – the time, x – the coordinate along TE conductor, $T(x, t)$ – the temperature of TE conductor, $j(t)$ – the current density in the TE conductor, $\rho = 1/\sigma$ – the specific resistivity, κ – the thermal conductivity, c_v – the specific heat, ρ_0 – the bulk density, also we denote $\chi = \kappa/c_v\rho_0$ – the thermal diffusivity.

The P-mode (Fig. 1a) boundary conditions are as follows

$$\begin{aligned} T(x,t)|_{x=0} &= \overline{T} - T_0\theta(t) \\ T(x,t)|_{x=l} &= \overline{T} + T_0\theta(t), \end{aligned} \tag{2}$$

where $\overline{T}$ – the external mean temperature, T_0 – the amplitude of variation of the external temperature, the function $\theta(t)$ is set to -1 on the even half-periods and on the odd ones is equal to +1

$$\theta(t) = \begin{cases} +1, & nP < t < (n+1/2)P \\ -1, & (n+1/2)P < t < (n+1)P \end{cases}. \tag{3}$$

The S-mode (Fig. 1b) corresponds to the case when the temperature of the ends (junctions) of TE conductor varies continuously according to sine wave, therefore the boundary conditions in the S-mode are

$$T(x,t)|_{x=\pm a} = \overline{T} \pm T_0\sin(\omega t), \tag{4}$$

where $\omega = 2\pi/P$ – the angular frequency of the temperature change, $\overline{T}$ and T_0 have the same meanings as in the P-mode.

Thus, during the period the TE conductor in P- and S-modes has the maximum temperature at the hot end (junction) $T_H = \overline{T} + T_0$ and minimal at cold end (junction) $T_C = \overline{T} - T_0$.