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An investigation on thermoelectric coolers operated with continuous current pulses

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ABSTRACT

This paper studies the refrigeration characteristics of a thermoelectric cooler (TEC) operated under continuous current pulses. A validated numerical model is used to obtain the temperature curves versus time. Obtained results reveal that applying a next current pulse before the complete recovery of temperature overshoot would cause an lift of the temperature curve over the next pulse. However, the temperature increment varies very similar to that of the first-order step response. After a few of current pulses, the temperature shows a varying trend completely periodical. Furthermore, shorter current period results in greater temperature increment and slighter supercooling effect. The shortest current period to achieve a periodical supercooling effect is greatly subject to the temperature overshoot because the maximum temperature drop is approximately identical in each subsequent current periods. Moreover, although the initial temperature increases as the cooling load increases, the temperature varying characteristics are highly similar for the different cooling loads. This indicates that the temperature curve of the first pulse is decisive in a continuous operation. Results obtained here show that the periodical supercooling effect could be achieved if the current period is properly designed.

1. Introduction

The performance of an electronic component is highly temperature-dependent [1–5]. However, with the decreasing feature size and increasing clock speed, in accordance with Moore's law, the design of microelectronics and optoelectronics is facing ever increasing challenges for thermal management [6]. For instance, heat generation from silicon microprocessors is with magnitude possibly greater than 300 W cm^{-2} and the heat flux of a semiconductor lasers may exceed 1000 W cm^{-2} [7].

Consequently, advanced cooling technology of electronic devices is essential in controlling the component temperature and realizing reliable operation. Numerous efforts have been devoted to the electronic cooling issues, such as optimal design of the heat sink [8–11], application of the liquid cooling heat sink [12–16] and other technologies [17–19]. Hajmohammadi et al. [9] performed a detailed optimization process conducive to the minimization of the peak temperature in a heat generating body. Chiu [12] numerically and experimentally investigates the heat transfer performance and characteristics of liquid cooling heatsink containing microchannels.

However, in addition to the high heat flux, electronic components also manifest features of producing transient hotspots that may vary temporally in heat flux, temperature, and location [7]. In this case, thermoelectric coolers (TECs) are being attractive solutions since they are capable of offering site-specific and on-demand localized active cooling of high heat flux region, which offer advantages over the other current passive cooling technologies.

Owing to the on-demand features of the electronics cooling mentioned above, the transient TEC cooling by using a current pulse become appealing for the electronic cooling [20–22]. As well known, a TEC pumps heat by utilizing the Peltier effect which accompanied by the Joule and Fourier effects. For a specific heat sink and heat flux (cooling load), the TEC provides a minimum cold side temperature at a certain steady current (optimum current I_{opt}). This minimum temperature is also limited by the properties of the thermoelectric materials used through the figure of merit, $z = \frac{\alpha^2}{\rho k}$, where α is the Seebeck coefficient, ρ is the electrical resistivity, and k is the thermal conductivity. However, when a current greater than I_{opt} suddenly applied to a TEC which is being operated at I_{opt}, an additional temperature drop will be achieved. This is called the supercooling effect. This phenomenon can be attributed to the intrinsic difference between the Peltier and Joule effect. As well known, the Peltier effect is a surface effect but the Joule heat

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Nomenclature

A	area (m^2)
a	fitting parameter
b	fitting parameter
c	heat capacity (W kg^{-1} K^{-1})
d	fitting parameter
T	temperature (°C or K)
ΔT	temperature difference (°C)
Δx	space discretization interval (m)
I	current (A)
K	thermal conductance (W K^{-1})
k	heat transfer coefficient (W m^{-2} K^{-1})
L	thickness (m)
N	number of TE couple pair
Q	cooling load (W)
q	heat flux (W m^{-2})
r	electrical resistivity (Ω m)
z	figure of merit (K^{-1})

Greeks symbols

α	Seebeck coefficient (V K^{-1})
$\Delta\tau$	time discretizetion interval (s)
λ	thermal conductivity (W K^{-1} m^{-1})
ρ	density (kg m^{-3})
τ	time (s)

Subscripts

1-6	computation domains
c	cold side
cp	current period
eff	effective
fh	cooling fluid at hot end
h	hot side
hs	heat sink
i	time node
init	initial
max	maximum
min	minimum
n	space node
opt	optimum
osh	overshoot
p	pulse
pd	pulse duration
rise	rise
s	steady
sc	supercooling

generated approximately uniformly throughout the whole TE elements. When the current steps to a greater magnitude, the intense cooling would occur at the cold side temporally before the Joule heat reaches. In this way, an improved temperature drop can be achieved over the steady current operation. However, the Joule heat accumulated during the greater current will finally reaches the cold side and leads to a cold side temperature even higher than the initial value, which is called the temperature overshoot.

The TEC transient or current pulse cooling is extensively studied [21–35]. Snyder et al. [32] attempted a thorough experimental investigation of a practical pulsed Peltier cooler to determine the minimum set of essential parameters and their relationships. They also used a physical basis to explain these relationships. Yang et al. [29] studied the transient response of thermoelectric coolers through examination of both the minimum temperature reached and the time constants involved in the cooling and the recovering stages. Gupta et al. [22] developed a detailed 3D thermal model of the electronic package and attached superlattice TEC devices to investigate the effect of both steady state and transient mode of operation of TEC on hot spot temperature reduction. Shen et al. [23] studied the transient characteristics of miniature TEC for laser cooling.

In brief, the TEC transient cooling by using current pulse is of great importance for the electronic cooling and causing increasing research interests. In fact, the Joule heat accumulated during a current pulse usually gives rise to a temperature overshoot of a TEC cold side, which would last for a much longer time relative to the time holding a supercooling effect. It is usually considered that the next current pulse should be applied after the temperature completely returns to the initial value. Nevertheless, few studies have demonstrated that applying a next current pulse before the complete recovery would results in the failure in the transient cooling operation. Actually, a supercooling effect would remain in such a case. Therefore, the cooling characteristics of a TEC mentioned above need to be further studied. In this paper, the cooling characteristics of a TEC operated under a continuous current pulse would be thoroughly investigated. Results obtained here will contribute to the design of a TEC used for electronics cooling.

2. The transient numerical model

A realistic TEC system consists of a heat spreader at the cold side, a TEC and a heat sink at the hot side, as shown in Fig. 1(a). The TEC comprises a number of p–n thermoelectric couples connected electrically in series but thermally in parallel and sandwiched between two electrically insulating but thermally conducting ceramic plates. Due to the slight difference among thermal characteristics of TE elements, temperature distributions in TE elements of a realistic TEC are almost the same. Therefore, only one TE element is considered in the modeling. The numerical analysis of the pulse cooling of a realistic TEC element can be handled as a one-dimensional problem as shown in Fig. 1(b). The material of the heat spreader and metal strips are selected to be aluminum. It is assumed that there are no interfacial thermal contact resistances between solid surfaces. Moreover, the temperature of the cooling fluid and the thermal conductance of the heat sink unit are kept to be constant in each simulation case.

An energy balance analysis for the TE element leads to the governing equation as follows [24]:

$$\rho_4 c_4 \frac{\partial T}{\partial \tau} = \lambda_4 \frac{\partial^2 T}{\partial x^2} + r_4 \frac{I^2}{A^2} \tag{1}$$

where ρ, c, λ and r are the density, heat capacity, thermal conductivity and electrical resistivity, respectively. I and A represent applied current and cross sectional area of TE element, respectively. Corresponding to Fig. 1(b), the subscript 4 refers to the fourth computational domain, i.e. TE element.

For other computational domains, the governing equations can be expressed as

$$\rho_j c_j \frac{\partial T}{\partial \tau} = \lambda_j \frac{\partial^2 T}{\partial x^2} \tag{2}$$