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A numerical study on the temperature overshoot characteristic of a realistic thermoelectric module under a current pulse operation

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ABSTRACT

This paper presents a detailed investigation on temperature overshoot characteristic of a realistic thermoelectric module (TEM) that operated with a square current pulse. A numerical model for TEM is developed and validated. Based on the model, obtained simulation results reveal that the transient temperature variation of realistic TEM cold side is more moderate due to the effect of the metal strips and the ceramic plates. Furthermore, the temperature overshoot characteristic of TEM cold side is analyzed for different current pulse parameters and operation conditions. For the square current pulse operation, the temperature overshoot occurs only when the current pulse amplitude is greater than a critical value, which is jointly determined by original steady current, cooling load and thermal conductance of heat sink. From the results obtained here, we propose a general principle to make a judgment whether a temperature overshoot will occur under a square current pulse operation. The present study will provide beneficial guidance for design of a TEM under current pulse operations.

1. Introduction

In 1958, Stilbans and Fedorovich [1] first reported the current pulse cooling effect in thermoelectric (TE) elements. For a thermoelectric element maintained at a steady temperature, the Peltier cooling being an interfacial effect is confined to the cold end of the element and the Joule heating is volumetric in nature. As well known, there exists an optimum current (I_{opt}) for a thermoelectric module (TEM) to provide a maximum temperature difference under a steady current operation [2,3]. If a current pulse with magnitude several times higher than the I_{opt} is imposed to the elements, intense cooling is achieved at the cold end due to the different effects. However, great amount of heat is accumulated throughout the whole TE elements during the current pulse. After reaching the minimum value, the cold side temperature begins to increase and usually exceed the original value, i.e. the temperature overshoot in pulse current operation.

After firstly reported, the phenomenon has been extensively investigated [4–21]. Miner et al. [7] introduced the concept of a thermoelectromechanical cooler, which modifies a traditional thermoelectric cooler by using intermittent contact of a mechanical element synchronized with an imposed pulsed current. Thonhauser et al. [12] investigated the influence of the pulse shape upon the transient cooling mechanism of free standing TE elements (without metal strips and ceramic plates). They found that using a quadratic pulse form provides a greater maximum temperature drop. Yang et al. [13] 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. Chakraborty et al. [14,15] presented general thermodynamic formulations which clearly map both useful and dissipative losses for the transient operation of a thermoelectric cooler (TEC).

However, the methodology utilized in most previously mentioned researches may be further improved. Yang et al. [10] indicate that, if the thermal conductance of heat sink is not be taken into account, it will cause obvious deviation between experimental data and simulation results of the cold junction temperature after the current pulse turned off. In addition, the cold end boundary condition is included with an assumption of cooling load being zero ($Q_c = 0$ W). Shen et al. [21] studied the impacts of Q_c at the cold-end and the convection heat transfer coefficient at the hot-end on the transient supercooling effect of voltage pulse in TEMs. They also found that a lower supercooling temperature at the cold-end may also be obtained when an original current lower than I_{opt} imposed to the TE element. Shen et al. stated that, however, ignoring the impacts of ceramic plates will give rise to discrepancies between numerical simulation results and experimental data [21].

In fact, there are two important issues should be addressed in the thermal management by utilizing a realistic TEM under current pulse operations. The one is the impacts of metal strips and ceramic plates. In a steady current operation, metal strips and ceramic

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Nomenclature

A	area (m^2)
c	heat capacity (W kg^{-1} K^{-1})
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 resistance (Ω)
r	electrical resistivity (Ω m)

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	cooled object
cj	cold junction
crit	critical
eff	effective
fh	cooling fluid at hot end
h	hot side
hs	heat sink
max	maximum
n	space node
opt	optimum
osh	overshoot
p	pulse
pd	pulse duration
pmax	maximum value during a pulse
pmin	minimum value during a pulse
ps	steady value corresponding to pulse level
s	steady
sc	supercooling

plates manifest themselves only in their thermal resistances which are very limited, or even negligible, compared with the resistances of TE elements. Nevertheless, it differs greatly from cases under current pulse operations. The metal strips and ceramic plates have thicknesses comparable to that of TE elements and heat capacities nearly four times of that of TE elements [22,23]. Thus, impacts of the metal strips and ceramic plates should be taking into account in the modeling of a realistic TEM under current pulse operations. The other issue is the temperature overshoot of the cold side temperature. Obviously, a temperature overshoot is undesirable for the cooled object. Although the temperature overshoot effects is observed for years, little attention has been devoted to the characteristics of this effect as previous researches mainly focus on other aspects.

In present paper, we develop a numerical model to capture the transient characteristic of a realistic TEM more accurately by taking into account the impacts of the metal strips and ceramic plates attached to the cold and hot side of the TE element. In addition, the influence of the cooling load and the thermal conductance of the heat sink are also involved. The numerical model will be validated by comparing the results obtained here with the experimental data reported in previous literature [23]. Furthermore, the characteristic of the cold side temperature overshoot under square current pulse is investigated in detail. It will be discussed that the influences of operating condition parameters on the temperature overshoots are not independent. By comprehensively considering the influence of the cooling load, thermal conductance of the heat sink and the amplitude of the current pulse, we propose a general principle to make a judgment whether a temperature overshoot will occur during or after a current pulse. The present study will provide important perspective into the characteristics of the temperature overshoot and contribute to the optimum design of a realistic TEM under current pulse operations.

2. Transient and steady models

A realistic TEM system consists of a heat spreader at the cold side, a TEM and a heat sink at the hot side, as shown in Fig. 1(a). The TEM is comprised of 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

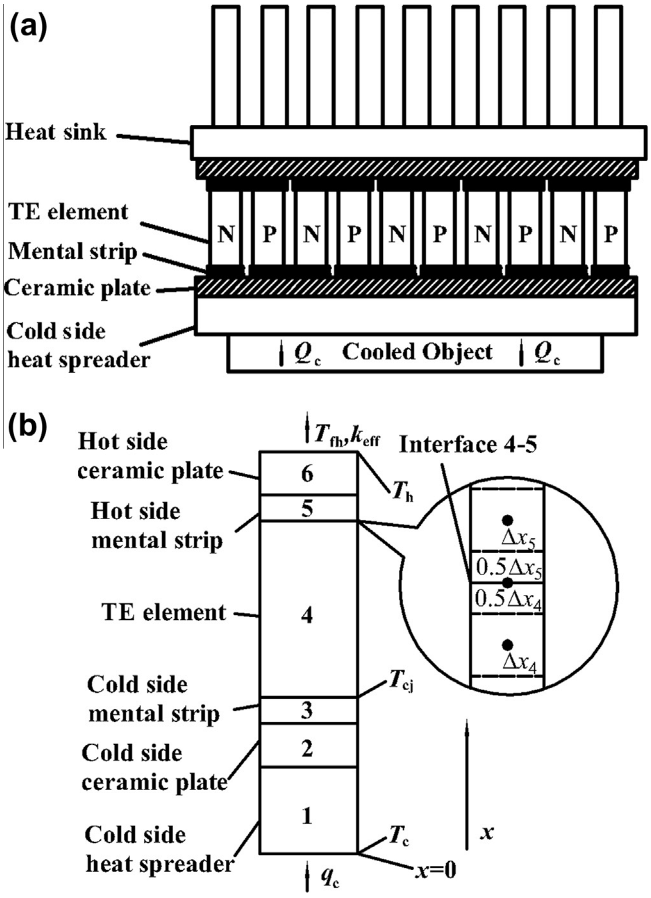

Fig. 1. Schematic diagrams of a realistic TEM system (a) and the corresponding computational domain (b).