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Improvement of transient supercooling of thermoelectric coolers through variable semiconductor cross-section

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HIGHLIGHTS

- A new TEC design with variable semiconductor cross-sectional area is proposed.
- A multiphysics model is used to study the transient supercooling of the new design.
- Two additional effects are found and can be used to improve transient supercooling.

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ABSTRACT

In this work, a new design of thermoelectric cooler (TEC) with variable semiconductor cross-sectional area is proposed to improve its transient supercooling characteristics. Four key evaluation indicators of transient supercooling for the conventional and new designs, including the minimum cold end temperature, maximum temperature overshoot, holding time of transient state, and recovery time ready for next steady-state, are examined and compared by a three-dimensional, transient, and multiphysics model. Two additional effects are observed in the TEC with variable semiconductor cross-sectional area. First, the variable cross-sectional area makes the thermal circuit asymmetric, so that Joule heat is preferentially conducted toward to the end with a larger cross-sectional area. Second, more Joule heat is produced close to the end with a smaller cross-sectional area. The present simulations find that these two effects can be utilized to achieve the desired evaluation indicators by changing the cross-sectional area ratio of hot end to cold end. When a lower cold end temperature, a smaller temperature overshoot, and/or a longer holding time are/is required, a larger cross-sectional area at the cold end is recommended. However, to achieve a shorter recovery time, a smaller cross-sectional area at the cold end is needed.

1. Introduction

Thermoelectric devices can convert heat into electricity by Seebeck effect or electricity into heat by Peltier effect. With the development of a new generation of nanostructured thermoelectric materials, figure of merit of materials is improved significantly, which promotes rapid growth of studies on thermoelectric devices [1–11]. Thermoelectric coolers (TECs) have been widely employed in various cooling and refrigeration applications [1–11]. Compared with conventional cooling technologies, TECs have many advantages such as high reliability, compact volume, layout flexibility, large operating temperature range, and rapid temperature response, because the coolers do not use any moving parts and environmentally harmful fluids [12,13].

When a TEC operates at steady state with a constant hot end temperature, the lowest cold end temperature achievable is determined by the figure of merit of semiconductor materials, TEC structure, and input current [14,15]. However, when a current pulse with magnitude several times larger than the optimal steady-state one is applied to the TEC, an instantaneously lower cold end temperature than that reachable at steady-state can be achieved. This phenomenon is referred to as transient supercooling, which can be applied in many fields where extra cooling for a short time is needed [16,17].

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At least five indicators can be used to evaluate the transient supercooling characteristics [16]: maximum cold end temperature drop $\Delta T_{c,max1} = T_{c,s} - T_{c,min}$, maximum temperature overshoot $\Delta T_{c,max2} = T_{c,max} - T_{c,s}$, time to reach the minimum cold end temperature t_{min}, holding time of the supercooling state Δt_{hold}, and recovery time to the next new steady state Δt_{rec}, where $T_{c,s}$ is the cold end temperature reachable at steady-state, $T_{c,min}$ and $T_{c,max}$ are respectively the minimum and maximum cold end temperatures reachable when a pulse current is applied to the TEC. In recent years, many efforts have been devoted to investigating the transient supercooling [16,18–30]. These investigations found that for a specific pulse shape, pulse amplitude and width have significant effects on the transient supercooling. Various pulse shapes were also compared in Refs. [16,31–35]. The results showed that there exists an optimal pulse shape to achieve the maximum cold end temperature drop, however, the optimal shape obtained in Refs. [16,31–35] are different. Recently, our group has developed a multiphysics transient TEC model to investigate the effect of pulse shape [36]. The results showed that the optimal shape is only determined by the time to reach the minimum cold end temperature and the pulse width (τ). For the pulses with $t_{min} < \tau$, a higher power pulse provides a lower cold end temperature, for the pulses with $t_{min} = \tau$, however, the trend is reversed. The results reasonably explained the divergence for the optimal pulse shape reported by the previous studies [16,31–35].

In the above studies [18–36], the p-type and n-type semiconductors were specified as regular cuboids or cylinders with constant cross-sectional areas. Hoyos et al. [37] proposed for the first time that it is possible to achieve a lower cold end temperature when variable semiconductor cross-sections are adopted. They fabricated a TEC with conical semiconductor legs and experimentally tested its transient supercooling characteristics. Their tests showed that with narrow pulse width and large amplitudes, additional cooling of the order of 45° below the steady-state maximum with recovery times in the range of 1–3 s was obtained. Following Hoyos et al.'s work, Yang et al. [16] developed a one-dimensional heat conduction model to investigate the transient supercooling performance of a axisymmetric TEC element with variable semiconductor cross-sectional area. Their results showed that a lower minimum transient temperature but a shorter holding time are observed for the tapered axisymmetric semiconductor legs with smaller cross-sectional area at the cold end. Thus, they concluded that the increase of holding time for TEC legs with a larger cross-sectional area at the cold end can be potentially useful for the device to be operated for a longer time.

It should be noted that in Yang et al.'s work, a freestanding TEC element was modeled with constant semiconductor properties, and only Joule heat was assumed as the internal heat source. Our previous study [36] has demonstrated that although the multiphysics model with constant and variable properties predict almost the same minimum cold end temperature, the model with constant properties underestimates the temperature overshoot by about 90 K. Accurate prediction of the temperature overshoot is very important for transient supercooling applications, because a larger temperature overshoot means that the TEC needs a longer time to return to the previous steady state. In additon, the larger temperature overshoot also could lead to burn-out of the electronic device that needs to be cooled. Thus, considering of variable properties is necessary for the accurate prediction of TEC transient supercooling performance. Furthermore, as expected, when the variable semiconductor cross-sectional areas are adopted, three-dimensional current and temperature distributions may occur in p–n junction and hence the one-dimensional model may be improper. In addition, an actual TEC element is composed of a p–n junction, three metallic connectors, and two electrically insulating ceramic plates. The ceramic plates have large heat capacity, hence, the transient response characteristics for the actual TEC element differs significantly from those for the freestanding TEC element.

Based on the above analysis, a rigorous and comprehensive study on TEC shape effect on transient supercooling characteristics is quite lacking up to now. Therefore, the objective of this work is to investigate how variable semiconductor cross-sectional area influences the transient supercooling characteristics. To achieve this objective, a complete, three-dimensional, and multiphysics TEC model is firstly used to predict the steady-state TEC performance. The optimal steady-state currents are respectively obtained for the TEC with constant and variable cross-sectional semiconductor areas. Then, a pulse current with an amplitude several times larger than the optimal steady-state current is applied to the TECs to investigate and compare their transient supercooling characteristics. Finally, the effects of pulse amplitude and area ratio of hot end to cold end on the transient supercooling characteristics are investigated.

2. TEC with variable semiconductor cross-sectional area

Generally, a TEC is composed of several tens or hundreds thermoelectric elements. These thermoelectric elements are connected thermally in parallel and electrically in series, and hence a thermoelectric element can be extracted as the computational domain (Fig. 1). The element consists of a p-type semiconductor leg, an n-type semiconductor leg, three metallic connectors, and two ceramic plates. Fig. 1(a) shows the schematic of a conventional TEC element, in which the thicknesses of ceramic plates, metallic connectors, and semiconductor legs are H_0, H_1, and H_2, respectively, the p- and n-type semiconductor legs have the same square cross-section with the area of $A_{semi} = L_2 \times L_2$, and the two ceramic plates have the same rectangular cross-section with the area of $A_{cer} = (2L_1 + 2L_2) \times L_2$. Fig. 1(b) shows the schematic of a TEC element with variable semiconductor cross-sectional areas, in which the cross-sectional areas for both the p-type and n-type semiconductor legs change linearly with the leg thickness, while the other

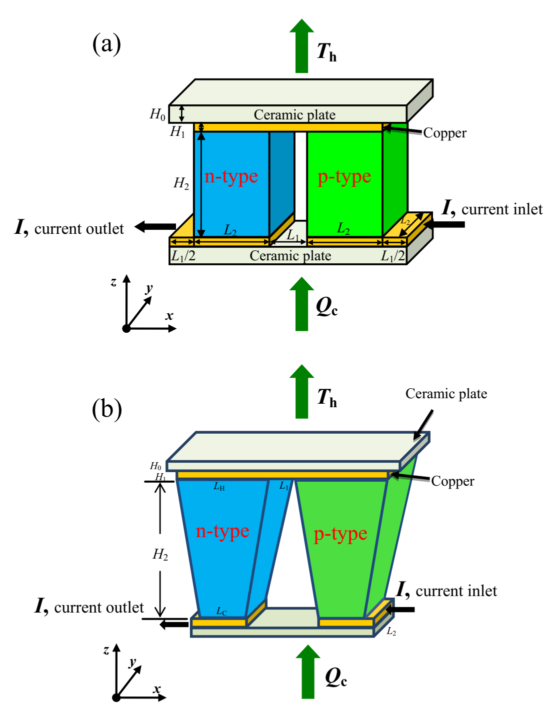

Fig. 1. Schematics of the TEC element: (a) with constant cross-section; (b) with variable cross-section.