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Enhancement of maximum temperature drop across thermoelectric cooler through two-stage design and transient supercooling effect

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HIGHLIGHTS

- A new design concept is proposed to enhance the maximum temperature drop across TECs.
- The design combines cascade TEC with transient supercooling effect.
- Effectiveness of the design is verified by a multiphysics and transient TEC model.
- Pulse parameters and TEC geometry are examined to further improve supercooling.

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ABSTRACT

In this work, a new design concept which combines two-stage design with transient supercooling effect is proposed to enhance the maximum temperature drop across thermoelectric coolers (TECs). A three-dimensional, multiphysics, and transient model is used to examine the design effectiveness. Step current pulses with various amplitudes (P) and widths (τ) are supplied to the two stages of a two-stage TEC in series. The results show that, as compared with the single-stage counterpart, a significant improvement in the maximum cold-end temperature drop ($\Delta T_{c,\max}$) is observed for the two-stage TEC. Meanwhile, the new design also greatly reduces the temperature overshoot ($T_{c,\max}$) and increases the holding time of supercooling state (Δt_{hold}). Subsequently, effects of the pulse amplitude, width, and shape are discussed and two important geometry parameters: the cross-sectional area ratio of p-type leg to n-type leg and the leg length ratio of cold stage to hot stage are investigated. These results confirm that $\Delta T_{c,\max}$, $T_{c,\max}$, and Δt_{hold} can be further improved by optimizing the pulse and the geometry parameters. This work provides a feasible cooling approach for some specific cooling targets, such as mid-infrared laser gas sensors or any other semiconductor devices which require a temporary but large temperature drop.

1. Introduction

In recent years, thermoelectric devices (TEs) have attracted great attention due to their promising applications in power generation [1–5], cooling [6–10], heating [2,11], waste heat recovery [12–15], and energy conversion [1,7,16]. Improvement of TEs performance for these energy-related applications could contribute to alleviating energy crisis and environment deterioration for the 21st century. The performance of TEs is not only determined by the figure-of-merit (ZT) of materials [1,16,17] but also dependent on TE structure design [5,6,9], operation condition [2,10], and external loading [10–12]. Up to now, a large amount of studies are conducted to make advancement in the area of TEs, a comprehensive literature survey can be presented by categorizing the subjects as analysis method development [4,18,19], material property characterization and analysis [4,16,17], modeling and parameters optimization [3,4,9,18,19], as well as structure design and modification [6,20,21]. Some recent review articles provided more details and summarized the promising potential and prospect of TEs [1,7,16,22].

When focusing to a certain application area, the advantage and the capability of TEs are specific. In cooling technologies, many electronic devices such as infrared detectors and semiconductor

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lasers require a stable low-temperature operating environment. As an active all-solid-state cooling technique with advantages of compact, high reliability, lightweight, low-cost operation, and direct electric energy conversion [22], thermoelectric coolers (TECs) have been widely used for temperature controlling and cooling purpose. For example, the integration of thermoelectric micro-coolers into high power laser diode was used as a real time and self-adapting temperature controller near the high heat flux regions to stabilize the temperature-dependent wave-lengths in laser beams [23].

The maximum temperature drop between the hot and the cold end is a very important evaluation index for TECs and it closely depends on the *ZT* of thermoelectric materials. However, it is extraordinarily challenging to find a material with a large *ZT*. As is well known, a single-stage TEC can provide at most 70 K maximum temperature drop when its hot end remains at room temperature [24]. Up to now, two methods have been proposed to elevate the maximum temperature drop across TECs. One is to adopt multi-stage design, where two or more thermoelectric modules are attacked on top of the other [25]. Another is to use transient supercooling effect, where a pulse current with magnitude several times larger than the optimal steady-state current is imposed to TECs [26].

Previous studies [24,25,27] have shown that a two- or multi-stage TEC can provide a temperature drop larger than 100 K due to additivity of the temperature drop produced by each stage. It was also found that the lowest cold-end temperature for a two-stage TEC could be further reduced by optimizing its geometric structure and operating conditions, such as the number ratio of thermoelectric elements between the two stages [8,9,20,24,25,27–35] and the current ratio between the two stages [8,24,25,27,28,30,34,36]. Similarly, the transient supercooling for a single-stage TEC has been investigated experimentally and numerically [21,37–43]. The increased maximum temperature drop was explained by interplay between Peltier cooling and Joule heating. The Peltier cooling occurs at the cold end while the Joule heating is distributed uniformly across the semiconductor leg. When a pulse current is supplied to the TEC, the Joule heating takes more time than the Peltier cooling to influence the cold-end temperature due to finite thermal diffusion rate; thus, a temporary temperature drop occurs on the cold end. The maximum cold-end temperature drop and the holding time of supercooling state for the transient supercooling were found to strongly depend on the pulse shape, width, and amplitude [21,37–43].

It should be noted that the two-stage design can elevate the maximum temperature drop across a TEC when the TEC operates under steady-state conditions; however, by means of the transient supercooling effect, a single-stage TEC is found to yield a temporary temperature drop on its cold end. Thus it can be expected reasonably that when a current pulse is supplied to a two-stage TEC, the maximum temperature drop would be further enlarged. Based on this expectation, a new design concept which combines the two-stage design with the transient supercooling effect is proposed in this work for the first time to increase the maximum temperature drop across the TECs. First, a three-dimensional, multiphysics, and transient TEC model is developed to examine the effectiveness of the new design concept. Then, dynamic response characteristics of the cold-end temperature for a two-stage TEC are examined at various pulse amplitudes, widths, and shapes. Finally, effects of the geometric structure of the TEC are discussed.

2. Geometry of the two-stage TEC

The two-stage TEC studied in this work is electrically connected in series and composed of a hot stage with m thermoelectric elements and a cold stage with n thermoelectric elements. The total element number is assumed to be $m + n = 30$, thus an element number ratio between the two stages can be defined as $r = m/n = m/(30 - m)$. Each element consists of a p-type semiconductor leg, an n-type semiconductor leg, three metal connectors, and two ceramic plates. The spacing between the p-type and the n-type leg is L_1. All of the legs have the same cross-sectional area $A_{\mathrm{leg}} = L_2 \times L_3$. The leg length is H_c on the cold stage and H_{h} on the hot stage. The total leg length is defined as $H_{\mathrm{total}} = H_c + H_h$, which keeps a constant value of 1.0 mm for all simulations. The thickness is H_{con} for the metallic connectors and H_{cer} for the ceramic plates. Thermoelectric materials $(\mathrm{Bi}_{0.25}\mathrm{Sb}_{0.75})_2\mathrm{Te}_3$ and $\mathrm{Bi}_2(\mathrm{Te}_{0.94}\mathrm{Se}_{0.06})_3$ with temperature-dependent material properties are selected as the p-type and the n-type leg, respectively. The connectors are made of Cu and the ceramic plates are made of $\mathrm{Al}_2\mathrm{O}_3$. All material properties can be found in Ref. [43].

Two specific two-stage TEC structures with different values of m and n are employed. The first structure has $r = m/n = 20/10 = 2$. Adopting this design is because that a two-stage TEC with more legs on its hot stage can yield a larger temperature drop when the TEC operates at steady state [27]. The second structure has the same leg number on each stage with $r = 15/15 = 1$. This design possesses characteristics of switch polarity so that it can be used in some specific applications. For example, thermoelectric air conditioner systems which can be conveniently hung on walls for building air-conditioning must be able to easily switch between cooling and heating to meet consumer's requirements [22,44–45]. In this condition, the hot and cold stages can interchange their roles in operation with the cooling capacity and COP remaining unchanged when the supplied electric current is alternated. For the purpose of comparison, transient supercooling characteristics is also simulated for a single-stage TEC. The leg length for the single-stage TEC is assumed to be 1.0 mm and the other geometry parameters are identical with those of the two-stage TECs. Thus, the single- and the two-stage TECs use the same amount of semiconductor materials. Considering that the thermal characteristics among the TEC elements are periodic, only one symmetric unit is modeled and illustrated in Fig. 1.

3. Numerical model

The three-dimensional multiphysics model developed in our previous studies [43,46] is used to simulate transient supercooling characteristics of the two-stage TEC unit. The following assumptions are made: the TEC operates under transient state conditions; the p-type and the n-type leg are modeled as two different parts; the material properties are temperature-dependent; the electric and the thermal contact resistance between any two adjacent materials are ignored; the heat losses to ambient are ignored.

It should be noted that the effect of contact resistances on TEC performance may play a significant role. However, with the advancement of semiconductor manufacturing technology, interface properties can be tailored by carefully selecting materials and film growth conditions to conceivably reduce the thermal and electrical contact resistance. In this condition, the effect of the contact resistance can be safely neglected. Based on this reason, the thermal and electric contact resistance is not included in the present model. The governing equations for the multiphysics model include energy equations and electric potential equations, and they are described as follows.

3.1. Energy equations

$$(\rho c_{\mathrm{p}})_i \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_i \nabla T) + \frac{J^2}{\sigma_i} - \beta_i \vec{J} \cdot \nabla T \tag{1}$$