Extends the Refrigeration Limit of a Thermoelectric Element Through Micro/Nano Scale Cooling

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Abstract: A new method was proposed to maximize the effective figure of thermoelectric cooling device (TECD) through introducing micro scale cooling at its hot end. A theoretical model was established to characterize such operational behaviors. Parametric studies were performed to test the effects of using various possible ways to improve the cooling capability. The results show that there exists an optimum cooling length for the TECD to realize a maximum temperature difference between its hot and cold legs. Implementations of the present method to the low temperature environment and several other specific situations were discussed. Some issues related to the fabrication of the structure were analyzed. Compared with the strategy of improving Z through innovating the material properties, this approach provides a new physical way of enhancing the cooling efficiency of the thermoelectric cooling element, when the material reached its limit.

Key words: chip cooling; heat transfer; micro/nano scale; multi-stage cooler; optimization; refrigeration limit; thermoelectric element

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基于微/纳尺度冷却扩展热电元件的制冷极限

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摘要：提出一种借助于在热电冷却器热端引入微尺度冷却，以提高其制冷性能参数的新方法，并建立了相应的理论模型来刻画该过程，并在此基础上对各类有助于提高制冷性能的潜在途径进行了参数化研究。结果表明，热电臂中存在一个最佳冷却长度，可在其冷热端实现最大的温度差。讨论了将该方法在低温环境及其他几类特殊场合的应用，并分析了加工该结构的相关问题。与通过改进材料来提高制冷性能的方法相比，该方法可在材料性能已趋极限时，提供一种新的物理途径用以强化热电冷却元件制冷性能。

关键词：芯片冷却；传热；微/纳尺度；多级制冷器；优化；制冷极限；热电元件

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1 Introduction

TECD has been widely used as a micro cooling device for electronic module in military, aerospace, instrument, and industrial or commercial products [1-4]. It offers the potential to enhance the cooling of electronic module packages by: (1) reducing chip operating temperatures at a given module heat load; (2) allowing higher module heat loads at a given temperature level. TECD also offers the advantages of being compact, quiet, and having no moving elements. In addition, its degree of cooling may be readily controlled by means of the electric current supplied to thermoelectric element. In general, the maximum temperature difference (ΔT_{max}) across a one-stage TECD has been well known as [1]

$$\Delta T_{max}=\frac{1}{2}ZT_c^2 \qquad (1)$$

where, T_c is the temperature at cold end of the thermoelectric element; and Z is the figure of merit of the element, which depends on the material properties and can be expressed as

$$Z=\frac{\alpha^2}{k\rho} \qquad (2)$$

where, α is the Seebeck coefficient; k is the thermal conductivity; and ρ is the electrical resistivity. The limiting factors that to prevent an efficient cooling can be illustrated as follows. First, a good TECD needs junctions with a large Seebeck coefficient or a large Peltier coefficient since they are proportional to each other [1]. Secondly, to maintain the temperature gradient between hot end (at temperature T_h) and cold end (at temperature T_c), the thermal conductivity for the thermoelectric materials should be as low as possible. Lastly, it requires that when the electric current runs through the circuit, a minimal thermal dissipation (Joule heating) should occur. Generally, this was achieved by using materials with low resistivity.

Nevertheless, practicability of this technology has been limited for many years due to lack of thermoelectric materials with high figure of merit. For a thermoelectric generator, for example, to achieve its high efficiency, it is desired to operate the thermoelectric generator device over large temperature differences and also to maximize the thermoelectric performance of the materials used to build the devices. A state-of-the-art thermoelectric cooler can produce at most a ΔT_{max} of about 70 K, when its hot end remains at room temperature. Though multi-stage TECD can achieve higher ΔT_{max}, the maximum ΔT_{max} currently available is below 120 K, when the hot end of the cooler is kept at 300 K [5]. One limit for higher temperature difference is that the figure of merit usually becomes smaller in low temperature. On the other hand, people believe that a thermodynamic efficiency of thermoelectric cooler can compete with liquid-compressed refrigeration cycle if its value of Z has an increase of four times of the current level. Many researches focus on the approach to improve the physical properties and the manufacturing technique of the thermoelectric material, aiming to realize a higher Z. A variety of promising strategies such as transport and confinement in nanowires and quantum dots, reduction of thermal conductivity in the direction perpendicular to superlattice planes, and optimization of ternary or quaternary chalcogenides and skutteridites have been investigated recently [6]. But characterization of potentially interesting thermoelectric materials, particularly samples consisting of low-dimensional structures, imposes a greater challenge. Even for bulk materials, thermal conductivity measurements are never easy and are prone to large uncertainty. For low-dimensional structures, thermal conductivity measurements appear rather trick [6].

In addition to the improvement of the thermoelectric material, physical approach and the systematical optimization of a thermoelectric cooler are equally important in designing a high-performance thermoelectric refrigerator [7] . This is however sometimes ignored by many researchers. One such way for improving efficiency by building a segmented device is proposed early in 1960 s [8-9], based on that the thermoelectric properties of materials are temperature dependent. The TECD is composed of different laminations, which are bonded together. Each layer is selected so that its Z peaks at the temperature as just anticipated there in that layer. For a given thermoelectric material, its values of Z peak only at one temperature. When building a TECD, it is desired that the selected thermoelectric materials should have large Z over the whole temperature scale across the two ends of the thermoelectric device. Although much work has been directed at the fabrication of such segmented structures, the segmented devices have not been very successful in comparison with multistage devices in the early endeavor, because of the bonding problems between different material layers. High contact resistance at the interfaces of these segments can dramatically reduce the efficiency of a generator. However, the method does have some new developments recently due to the improvements of the fabrication capability [10-12] . Another approach reported is thermoelectromechanical refrigeration based on transient thermoelectric effects. The theoretical work shows that the method can effectively increase the thermoelectric figure of merit for maximum temperature difference applications by a factor of 1.8 [3] . Some other optimizations were also used in practical design of thermoelectric refrigerators [14-16] . Basically, all these methods can be classified into four kinds: matching of the property and temperature, matching the performance of the n- and p-doped elements, increasing the number of the stages, decreasing the heat flux flow to the cold end of the thermoelectric element.

Note that there exists temperature difference between the hot ends of thermoelectric elements and the coolant, a possible improvement on the apparent cooling performance can be achieved by cooling not only the hot surface of the thermoelectric cooler, but also some of its interior parts, a small space. As shown in Fig.1, the coolant with a temperature of T_0 was used to cool the hot surface of the thermoelectric refrigerator. One can find that the temperature at part of thermocouples at the right hand side of line 1 will be higher than that of coolant. Therefore, the cooler will work more effectively if certain coolant was particularly introduced to cool part of the thermocouples. Such method would reduce the heat flux flowing to the cold end of the thermoelectric elements. From the view of the micro scale heat transfer, it reduces the effective thermal conductivity k, which will therefore enlarge the effective figure of merit (see Eq. (2)) . To better understand the operation of this method, we will present a theoretical analysis on the heat transfer behavior and thus evaluate the cooling capability of the constructed structure.

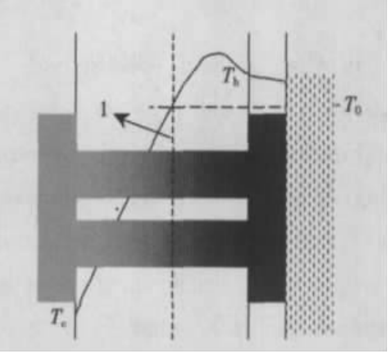

Fig.1 A sketch map of temperature changing along the longitudinal direction of the thermoelectric elements

图1 沿热电臂长度方向的温度变化示意图

2 Physical model and solution

For brevity, it is assumed that all the physical properties for the n- and p-doped elements are identical except that $\alpha_p=-\alpha_n=\alpha$. The thermoelectric element has a length l, perimeter P, cross-sectional area S, and thermal conductivity k. The length of the hot part of element to be cooled by the coolant is prescribed at a. The temperature of the coolant is fixed at T_0. The convection coefficient is h (see Fig.2). Assuming that the temperature in each cross-section of the n- or p-doped thermoelectric element is uniform, then the energy balance equations along the longitudinal direction of the bulk elements can be expressed as

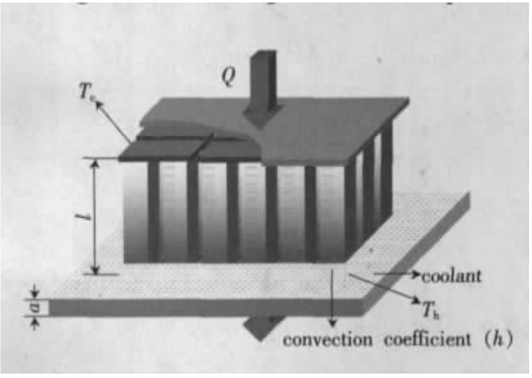

Fig.2 3D graph demonstrating the local cooling operation at the hot part of the thermoelectric cooler

图2 对热电制冷器热臂实施局部冷却的三维示意图

$$\frac{d^2T}{dx^2}+\frac{I^2\rho}{kS^2}-\frac{hP}{kS}(T-T_0)=0,\quad 0\le x\le a \tag{3a}$$

$$\frac{d^2T}{dx^2}+\frac{I^2\rho}{kS^2}=0,\quad a\le x\le l \tag{3b}$$

where, I is the electric current and ρ is the electric resistivity of the elements, respectively. The first two terms on the left-hand side of Eqs. (3a, b) represent thermal diffusion and electrical heating, respectively. The third term in the Eq. (3a) is for the heat removed by the coolant.

The boundary conditions at the hot and cold ends of the elements are prescribed as

$$\begin{aligned} T|_{x=0}&=T_h\\ T|_{x=l}&=T_c \end{aligned} \tag{4}$$

Since the temperature and thermal flux of the elements are continuous at the section of $x=a$, this yields

$$\begin{aligned} T|_{x=a^-}&=T|_{x=a^+}\\ \left.\frac{dT}{dx}\right|_{x=a^-}&=\left.\frac{dT}{dx}\right|_{x=a^+} \end{aligned} \tag{5}$$

Solution to Eqs. (3a) and (3b) can easily be obtained as

$$T=\begin{cases} C_0e^{\sqrt{A}x}+C_1e^{-\sqrt{A}x}+\dfrac{B}{A},\ 0\le x\le a\\ -\dfrac{D}{2}x^2+C_2x+C_3,\ a\le x\le l \end{cases} \tag{6}$$

where, C_1, C_2, C_3, C_4 can be determined by Eq. (4) and Eq. (5). The aim of the present solution is to find out the maximum temperature difference over the thermoelectric element. One can obtain the heat flux flowing into the cold end of the thermoelectric element, which is

$$Q_{hc}=-kS\left.\frac{dT}{dx}\right|_{x=l}=kS(Dl-C_2)=kS\left\{\frac{D}{2}(l-a)+\frac{\left(T_0-T_c+\frac{D}{A}\right)[\cosh(\sqrt{A}a)-1]+\frac{D(l-a)}{2\sqrt{A}}\sinh(\sqrt{A}a)+T_h-T_c}{(l-a)\cosh(\sqrt{A}a)+\frac{1}{\sqrt{A}}\sinh(\sqrt{A}a)}\right\} \tag{7}$$

here,

$$A=\frac{hP}{kS}$$

$$D=\frac{I^2\rho}{kS^2}$$

According to the theory of the TECD, the quantity of the thermoelectric refrigeration Q_0 can be expressed as [1-2]

$$Q_0=\alpha IT_c-Q_{hc} \tag{8}$$

where, α is the Seebeck coefficient of the elements; I is the electric current and T_c is the temperature at the cold end of the elements.

Substituting Eq. (7) into Eq. (8), one gets

$$\Delta T=\left[\frac{\alpha IT_c-Q_0}{kS}-\frac{D}{2}(l-a)\right]\cdot\left[(l-a)\cosh(\sqrt{A}a)+\frac{1}{\sqrt{A}}\sinh(\sqrt{A}a)\right]-\left\{\left(\frac{D}{A}+T_0-T_c\right)[\cosh(\sqrt{A}a)-1]+\frac{D(l-a)}{2\sqrt{A}}\sinh(\sqrt{A}a)\right\} \tag{9}$$

It indicates that the maximum temperature difference will be gained when the quantity of thermoelectric refrigeration Q_0 is zero, which means the cold junction is in an adiabatic condition. The corresponding electrical current for this case is therefore obtained as

$$I=\frac{\alpha S T_c}{\rho}\cdot\frac{A(l-a)\cosh(\sqrt{A}\,a)+\sqrt{A}\sinh(\sqrt{A}\,a)}{[2+A(l-a)^2]\cosh(\sqrt{A}\,a)+2(l-a)\sqrt{A}\sinh(\sqrt{A}\,a)-2} \quad (0)$$

Then one gets the maximum temperature difference,

$$\Delta T_{max}=\left[\cosh\left(\frac{a}{l}\sqrt{Al^2}\right)-1\right](T_c-T_0)+\frac{1}{2}ZT_c^2\cdot\frac{\left[\left(1-\frac{a}{l}\right)\sqrt{Al^2}\cosh\left(\frac{a}{l}\sqrt{Al^2}\right)+\sinh\left(\frac{a}{l}\sqrt{Al^2}\right)\right]^2}{\left[2+Al^2\left(1-\frac{a}{l}\right)^2\right]\cosh\left(\frac{a}{l}\sqrt{Al^2}\right)+2\left(1-\frac{a}{l}\right)\sqrt{Al^2}\sinh\left(\frac{a}{l}\sqrt{Al^2}\right)-2} \quad (1)$$

Based on the expression of the maximum temperature difference $\Delta T_{max}=f\left(\frac{a}{l},Al^2,Z,T_c,T_0\right)$, one can analyze its dependence on the variables of $\frac{a}{l}$, Al^2, Z, T_c, and T_0, etc.

3 Results and discussion

A series of basic physical parameters for the commercially available thermoelectric cooler are used in this study. However, some parameters were varied in the calculations for testing their effects on the refrigeration performances. The standard parameters used in the analysis are listed in Table 1 [7]. Unless it was particularly mentioned, the parameters in the calculation are all taken from this table.

Table 1 Geometry and properties of the thermoelectric elements

表1 热电元件的几何尺寸及物性

α/ μV·K^{-1}	ρ/ Ω·cm	k/ (mW·K^{-1}·cm^{-1})	l/ mm	d/ mm	T_c/ K	h/ (W·K^{-1}·m^{-2})	(T_h-T_0)/ K
210	0.001	18	6	2.8	230	100	5

It has been assumed that all physical properties for the n- and p-doped elements are identical except $\alpha_p=-\alpha_n=\alpha$. The cross-section for the thermoelectric element is assumed as square with a side length d. The effective figure of merit of the thermoelectric element can be defined as

$$Z_{eff}=2\Delta T_{max}/T_c^2 \quad (2)$$

The present calculation is to investigate the trend of the effective figure of merit for the thermoelectric element under different conditions. Therefore we choose to characterize the cooling ability of improvement by the value of the ratio (Z_{eff}/Z). Obviously, as indicated by Eqs. () and (1), a large ratio Z_{eff} corresponds to a maximum temperature difference when the temperature at the cold end is fixed. Fig.3~9 present the improvement of cooling ability of the thermoelectric elements subject to different conditions. Overall, with the cooling at the part near the hot end of the thermoelectric elements, there appears a maximum Z_{eff}/Z, which in most situations is larger than 1. The ratio of Z_{eff} and Z approaches 1 when a/l becomes close to zero, which is true since Z_{eff}/Z when no coolant was applied to cool the elements. This ratio increases with the increase of the a/l. After reaching its peak value, the ratio gradually drops down when a/l keeps increasing. This is because the coolant temperature is higher than the thermoelectric element beyond this limit. Therefore the coolant will just serve to heat the TECD there but not to cool it. The length a allowing for $Z_{eff}/Z\geqslant 1$ can be called as effective cooling length. One can notice that this length does not fall in a narrow rage. Therefore a possible practical cooling length is easy to control. For different conditions, the improvements of Z_{eff}/Z and effective cooling length are also different. One note must be pointed out is that the result given in the figures is not practical when $a/l=1$. This is because the “coolant” heating the cool end must be considered when the whole thermoelectric element was inserted into the coolant.

The length l has important effect on the ratio, which is shown in Fig.3. The longer l, the higher maximum of Z_{eff}/Z and the shorter effective cooling length. So the method proposed in this paper is more effective when thermoelectric element has a long leg. Another important parameter to determine the performance of TECD is k. As shown in Fig.4, a higher Z_{eff}/Z can be gained when k increases. The ratio Z_{eff}/Z has the same dependence on the parameter ρ as indicated in Fig.5, but appears much evident. Z_{eff}/Z increases 20 percent when resistivity (ρ) increases by ten times. And the opposite dependence on the parameter α is shown in Fig.6. For $Z=\frac{\alpha^2}{k\rho}$ and the electric current exhibited in Figs. 4, 5, 6. it can be concluded that for a smaller Z, the method has the advantage of improving cooling ability. The method proposed here is not as effective as the approach by improving Z, but seems to be appropriate for the current level of the Z. A big problem in a thermoelectric cooling at very low temperatures is the falling down of the figure of merit of the thermoelectric material [8-20]. In such case, innovating the mate-

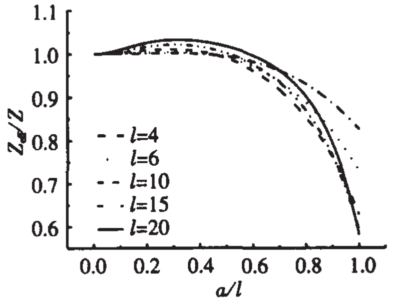

Fig.3 Z_{eff}/Z as a function of dimensionless element length cooled by the coolant and under different element length

图3 不同制冷元件长度下Z_{eff}/Z随无量纲冷却剂冷却长度的变化情况

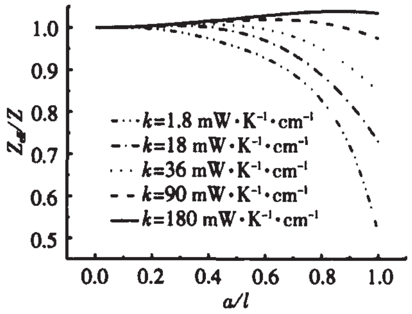

Fig.4 Z_{eff}/Z as a function of dimensionless element length cooled by the coolant and under different thermal conductivities for the thermoelectric element

图4 Z_{eff}/Z在不同热电元件热导率情况下随冷却长度的变化

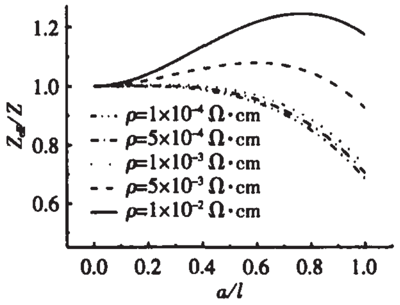

Fig.5 Z_{eff}/Z as a function of dimensionless element length cooled by the coolant and under different resistivities of the thermoelectric element

图5 Z_{eff}/Z在不同热电元件电阻率大小下随冷却长度的变化

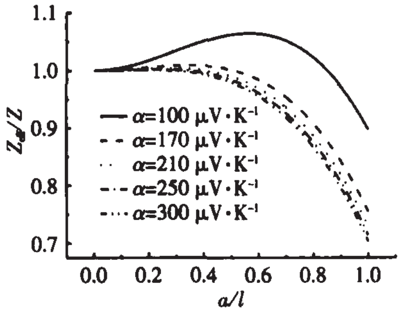

Fig.6 Z_{eff}/Z as a function of dimensionless element length cooled by the coolant and under different Seebeck coefficients

图6 Z_{eff}/Z在不同热电Seebeck系数下随冷却长度的变化

rial property often helps little. However, incorporating the increased cooling at the hot end of the thermoelectric element will definitely improve its figure of merit. Therefore the present method provides an alternative way for this situation.

The parameter h reflects the heat exchange between the coolant and the thermoelectric elements. It can vary in a wide range for the forced convection. And for micro/nano channel heat exchange, h can be even higher [11]. For the present method, improving h is a valuable way as seen from the Fig.7. This can be expected from our model since the target here is to cool the part hotter than the coolant and thus to decrease the heat flux flow to the cold end of the thermoelectric element. Another parameter $\frac{P}{S}$ has the same influence as that of h because both of them are parts of the dimensionless parameter Al^2. If cross-section is the shape of a gear or a strip or even complex fractal, the $\frac{P}{S}$ may increase significantly, it will be valuable for increasing cooling temperature difference. The multiplication of the h and $\frac{P}{S}$ could be considered as one parameter $\left(\frac{hP}{S}\right)$, which reflects the overall heat exchange between the coolant and the thermoelectric elements.

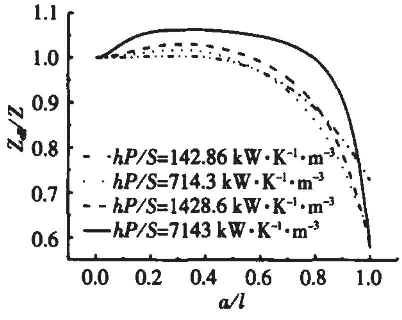

Fig.7 Z_{eff}/Z as a function of dimensionless element length cooled by the coolant and under different thermal and geometrical parameters

图7 Z_{eff}/Z在不同热学及几何参数下随冷却长度的变化示意图

The higher temperature difference between the coolant and the elements, the more sufficient heat exchange will be between them. Fig.8 depicts this effect to improve the refrigeration performance of TECD. With a higher T_h-T_0, the maximum of Z increases evidently. In fact, $T_h-T_0>0$ is the basic request for the present method. Otherwise if $T_h=T_0$, the "coolant" will heat the whole thermoelectric elements and the method will not be useful. But for a real thermoelectric cooler, it is impossible for $T_h=T_0$ since heat resistance always exists in the junction, hot plate, and the boundary layer of convection.

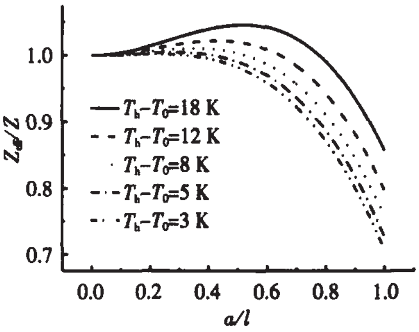

Fig.8 Z_{eff}/Z as a function of dimensionless element length cooled by the coolant and under different temperature differences between the hot end of the element and the coolant

图8 Z_{eff}/Z在不同热端与冷却剂温差条件下随冷却长度的变化

Fig.9 seems present a very attractive result for the ratio reaching the 1.41 when T_c=80 K. In the calculation, we assume that the physical properties keep unchanged. But Z usually is smaller in low temperature and a better result will therefore be achieved. On the other hand, if Z becomes higher, the maximum of Z_{eff}/Z is decreased, which is shown by the dashed curve in Fig.9. One must notice that in low temperature the maximum temperature difference between the hot end and the cold end is lower. For example at T_c=80 K, $T_h-T_c=\frac{1}{2}ZT_c^2=0.5\times0.00245\times80^2\approx7.8$ K. So T_h-T_0=5 K in our calculation is a comparatively larger value in this low temperature condition. One can say that the present method is a solution to improve the current cooling level of the TECD. Applying thermoelectric materials with a higher Z is a very efficient way, but it is limited by the currently available materials.

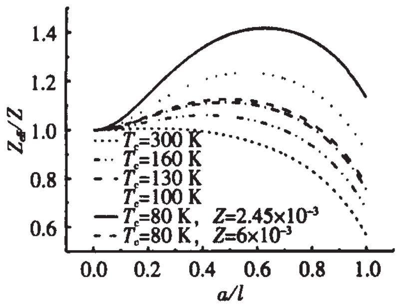

Fig.9 Z_{eff}/Z as a function of dimensionless element length cooled by the coolant and under different temperatures at the cold end of the thermoelectric element

图 9 Z_{eff}/Z 在热电元件不同冷端温度条件下随冷却长度的变化

A shortcoming of the present method is that it may increase the complexity of the thermoelectric cooler system. And the choice for the coolant is also a problem. The coolant must be clean and insulating. Despite of those disadvantages, the method could still be tried in the situation requesting a high temperature difference, such as in superconducting magnet systems [22-24]. Another advantage of this method is to decrease the current of the TECD. If a=0, I in Eq. (0) can be simplified as $\frac{\alpha T_c}{R}$, which can be easily proved to be larger than its value in the original expression. Here R is the resistance of the element.

The present concept can also be useful for the multi-stage TECD. For example, assuming a two-stage TECD with coolant applied on the first stage and the thermocouples at two stages are electrically separated, the temperature difference is then obtained as

$$\Delta T=\Delta T_1+\Delta T_2 \tag{3}$$

and

$$\Delta T_1=\frac{\alpha I_1 T_c}{kS}-\frac{D_1 l_1}{2} \tag{4}$$

$$\Delta T_2=\left[\frac{\alpha I_2(\Delta T_1+T_c)}{kS}-\frac{n_1}{n_2}\frac{\alpha I_1\Delta T_1+I_1^2R_1}{kS}-\frac{D_2}{2}(l_2-a)\right]\cdot\left[(l_2-a)\cosh(\sqrt{A_2}a)+\frac{1}{\sqrt{A_2}}\sinh(\sqrt{A_2}a)\right]-\left\{\left(\frac{D_2}{A_2}+T_0-T_c-\Delta T_1\right)\left[\cosh(\sqrt{A_2}a)-1\right]+\frac{D_2(l_2-a)}{2\sqrt{A_2}}\sinh(\sqrt{A_2}a)\right\} \tag{5}$$

where, subscript "2" represents the parameters of the base stage of the TECD, subscript "1" the parameters of the other stage and n the number of the elements in each stage. Since ΔT is a function of the current I_0 and I_1, the maximum temperature difference can be obtained through mathematic analysis and a more evidently improved refrigeration limit can be expected. Detailed analysis can be performed in future research and more complex cooling patterns such as cooling more than one stage's hot parts can be discussed.

4 Conclusion

Improvement of cooling efficiency of the TECD by selectively cooling the micro scale hot part of the thermocouples in a thermoelectric refrigerator is proposed. Its potential implementations in different conditions were analyzed by establishing a theoretical model. The results indicate that improvement can be achieved in different degrees. There is an optimum cooling length under various conditions for the maximum temperature difference. Thermoelectric elements with long leg-length, small Z and high convection coefficient h are beneficial for realizing a high temperature difference. The most possible application of the present TECD structure is for the low temperature environment. For a high-performance thermoelectric cooler, designing is as important as seeking new thermoelectric materials, especially for practical purpose. Compared with improved Z, the present method offers a new alternative way to improve cooling efficiency of the TECD. Meanwhile, it also opens many interesting issues in micro/nano scale heat and fluidic sciences.

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