Performance analysis of multi thermoelectric cooling modules

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Abstract—In engineering applications, multiple thermoelectric cooling (TEC) chips may be used together for a variety of reasons. This paper proposes a method for calculating the cold end temperature of a multi-chip thermoelectric cooling module that integrates the classical model of thermoelectric cooling and the thermal resistance matrix method, and compares the results of theoretical calculations and simulation analysis with the example of a four-chip thermoelectric cooling module.

1. Introduction

Thermoelectric refrigeration is also known as temperature differential electric refrigeration, or semiconductor refrigeration. It converts electrical energy directly into thermal energy through the Peltiereffect. Compared with traditional compressed refrigeration, thermoelectric refrigeration has many advantages, such as no transmission parts, no noise and pollution problems, small size, and compact structure. Therefore, thermoelectric cooling is very suitable to solve the cooling problems of small volume electronic equipment, medical devices, etc[1-3].

At present, the research on improving the performance of thermoelectric refrigeration system at home and abroad mainly has two general directions: (1) the optimization of the thermoelectric refrigeration sheet itself, such as the research on the new thermoelectric materials with high quality coefficient[4,5], and the optimization of the structure of the thermoelectric arm[6,7], and even the research on the multistage thermoelectric refrigeration sheet[8]; (2) Optimization of thermal design of thermoelectric refrigeration modules, such as optimization of heat dissipation performance of cold and hot ends[9,10], and distribution of heat dissipation capacity of cold and hot ends[11]. Some other related studies are also worthy of attention, such as the study on the physical and mathematical model of thermoelectric refrigerating sheets[12-14] and the influence of non-uniform temperature distribution on the performance of thermoelectric refrigerating sheets[15,16]. Influence of unsteady current on performance of thermoelectric refrigerating sheet[17,18]; in addition, the performance evaluation of the thermoelectric refrigerating sheet and how to choose the appropriate thermoelectric refrigerating sheet for the corresponding working conditions[19] are also discussed.

In practical work, the need for large cooling capacity is often encountered, and the single thermoelectric refrigeration sheet can not meet the situation, this is the need to arrange multiple thermoelectric refrigeration sheets in a certain way to use together, or parallel or series or separate power supply, but this aspect of the research is less. Therefore, the author believes that, in today's increasingly common multi-thermoelectric refrigeration module, it is necessary to refer to previous
scholars' research and methods on diffusion thermal resistance and thermal coupling of single chip and multi-chip[20,21], and carry out similar research on multi-thermoelectric refrigeration module.

In this paper, based on the classical model of thermoelectric refrigerating sheet and the thermal resistance matrix method, a method for calculating the parameters related to the working performance of the refrigeration module of multi-thermoelectric refrigerating sheet is proposed, and the finite element analysis method is used to carry out the simulation, and the results of theoretical calculation and simulation are compared. This method may provide reference for the optimization of the arrangement mode and power supply mode of the multi-thermoelectric refrigeration module.

2. Finite element simulation model

This paper takes the DA (Direct to Air) thermoelectric refrigeration module of four thermoelectric refrigerators as an example to introduce the theoretical calculation method and simulation.

The commercial software FLOTHERM commonly used in the field of thermal design was used for the finite element simulation analysis. The simulation analysis model is shown in Fig.1.

![Fig.1 The simulation model of a multi thermoelectric cooling module](image)

The relevant geometric parameters and material parameters of the simulation analysis model are shown in Tab.1 and 2, and the relevant parameters of the thermoelectric refrigerating sheet are shown in Tab.3.

| Tab.1 The geometrical parameters of the simulation model |
|--------------------------------------------------------|
| parameter                              value          |
| Size of the heat source/mm              100 × 100 × 5 |
| Size of the heatsinks/mm                100 × 100 × 100 |
| thickness of heat sink/mm               2              |
| Number of heat sinks                    22             |
| thickness of base/mm                    5              |
| Inlet size /mm                         110 × 100       |
Tab.2 The material parameters of the simulation model

| Material                  | Heat conductivity coefficient/ W/mK |
|---------------------------|-------------------------------------|
| Heat source copper        | 385                                 |
| Thermal insulating layer  | 0.05                                |
| Heat sinks copper         | 385                                 |

Tab.3 The parameters of thermoelectric cooling

| Parameter   | TEC1       | TEC2       |
|-------------|------------|------------|
| Geometry size/mm | 20 × 20 × 4.7 | 20 × 20 × 3.2 |
| $T_{ho}$/°C   | 50         | 50         |
| $Q_{max}$/W   | 8.4        | 12.8       |
| $\Delta T_{max}$/°C | 77.9      | 77.9       |
| $I_{max}$/A   | 3.8        | 5.8        |
| $V_{max}$/V   | 3.7        | 3.7        |

The arrangement of thermoelectric refrigerating sheets is shown in Fig.2:

(a) Row 1: Horizontal and longitudinal spacing of heat sources is 30
(b) Row 2: Horizontal and longitudinal spacing of heat sources is 0

Fig.2 The arrangement of thermoelectric cooling

Other Settings and basic assumptions of the simulation model:
(1) The ambient temperature is set as 30 °C and the ambient pressure is 1 ATM.
(2) The inlet air volume is 100 CFM, and the turbulence model uses automatic algebraic model.
(3) Assume that all surfaces are in perfect contact, without considering the contact thermal resistance;
(4) Radiation heat transfer is ignored.

3. Theoretical calculation model
The heat transfer process of DA type thermoelectric refrigerating module of multi-thermoelectric refrigerating sheet can be divided into three parts: (1) heat absorption at the cold end of the thermoelectric refrigerating sheet; (2) the thermoelectric effect inside the thermoelectric refrigeration sheet; (3) heat dissipation at the hot end of the thermoelectric refrigeration sheet.
Fig. 3 Schematic of multi thermoelectric cooling module and the corresponding thermal resistance network

(1) cold end heat absorption process of thermoelectric refrigeration sheet

The simulation results show that the heat absorption at the cold end of the thermoelectric refrigeration sheet is proportional to the heating power of the heat source, that is:

$$Q_c = kP + b$$  \quad (1)

Wherein, $Q_c$ is the heat absorption at the cold end of the thermoelectric refrigeration sheet, $P$ is the heating power of the heat source, $k$ is the proportional coefficient, and $b$ is the constant term.

Taking TEC1 of four thermoelectric refrigerating sheets arranged in arrangement 1 as an example, the variation curve of the heat absorption at the cold end of the four thermoelectric refrigerating sheets with the heating power of the heat source is shown in Fig. 4 below.

(a) TEC 1  
(b) TEC 2
(2) the thermoelectric effect process inside the thermoelectric refrigeration sheet

Member of the Soviet union Ioffe integration parr post effect, seebeck effect, Thomson effect, Fourier effect, and the material physical properties, thermoelectric performance often finishing out of the classical theory of thermoelectric cooling modules energy conversion, the energy conservation equation [22], hot and cold end this theory is still widely used in thermoelectric materials performance evaluation and optimization of thermoelectric refrigeration in areas such as:

\[ Q_{c} = N(\alpha I T_{c} - \frac{I^2 \rho}{2G} - kG(T_h - T_c)) \]  

\[ Q_{h} = N(\alpha I T_{h} + \frac{I^2 \rho}{2G} - kG(T_h - T_c)) \]

Where, \( N \) is the logarithm of thermoelectric arm; \( I \) is the working current of thermoelectric refrigerating sheet; \( T_c \) and \( T_h \) are the temperature of the hot and cold ends of the thermoelectric refrigerating sheet respectively. \( G \) is the geometric factor of thermoelectric arm; \( \alpha \), \( \rho \) and \( \lambda \) are Seebeck's coefficient, resistivity and thermal conductivity of thermoelectric materials, respectively.

Make the following conversion, so that:

\[ R_{m} = \frac{N \rho}{2G} \]  

\[ K_{m} = NkG \]  

\[ S_{m} = N\alpha \]

Equations (1) and (2) are converted into:

\[ Q_c = S_m I T_c - \frac{1}{2} I^2 R_m - K_m \Delta T \]  

\[ Q_h = S_m I T_h + \frac{1}{2} I^2 R_m - K_m \Delta T \]

Where \( \Delta T \) is the temperature difference between the cold and hot ends of the thermoelectric refrigeration sheet, and \( R_m \), \( K_m \) and \( S_m \) can be understood as the total resistance, total thermal conductivity and total Seebeck coefficient of the thermoelectric refrigeration sheet. These three parameters can be calculated by the performance parameters of the thermoelectric refrigeration sheet, \( I_{\text{max}}, V_{\text{max}}, \Delta T_{\text{max}}, Q_{\text{cmax}} \) and \( T_{\text{h0}} \). Where \( \Delta T_{\text{max}} \) is the maximum temperature difference between the cold and the hot ends that the thermoelectric refrigeration piece can reach when the hot end temperature of the thermoelectric refrigeration piece is \( T_{\text{h0}}, I_{\text{max}} \) and \( V_{\text{max}} \) are the working current and working voltage of the thermoelectric refrigeration piece at this time, and \( Q_{\text{cmax}} \) is the heat absorption at the cold end of the thermoelectric refrigeration piece when \( I=I_{\text{max}}, \Delta T=0 \). \( S_m, R_m \) and \( K_m \) can be expressed as [23]:

![Figure 4 Heat absorption at the cold side of thermoelectric cooling](image)
\[ R_m = \frac{(T_{h0} - \Delta T_{max})V_{max}}{T_{h0}I_{max}} \]  

(9)

\[ K_m = \frac{(T_{h0} - \Delta T_{max})V_{max}I_{max}}{2T_{h0}\Delta T_{max}} \]  

(10)

\[ S_m = \frac{V_{max}}{T_{h0}} \]  

(11)

(3) the heat dissipation process of the hot end of the thermoelectric refrigeration sheet

Referring to the relevant research and methods of multi-chip heat sources, this paper uses the thermal resistance matrix [24] to describe the heat dissipation process at the hot end of the thermoelectric refrigeration module of the multi-thermoelectric refrigeration sheet.

According to the principle of linear superposition, the thermal resistance matrix of multi-heat source components can be defined. The principle of linear superposition states that the temperature rise at node I of the heat source relative to the outside world is equal to the sum of the temperature rise caused by each heat source acting alone. The temperature of each heat source including n heat sources can be calculated by Equation (12):

\[
[R_d]^{n,n} \begin{bmatrix} Q_0 \\ \vdots \\ Q_l \\ \vdots \\ Q_n \end{bmatrix} + T_a = \begin{bmatrix} T_i \\ \vdots \\ T_i \end{bmatrix}
\]  

(12)

Where, \( Q \) is the heating power of each heat source; \( T \) is the temperature of each heat source; \( T_a \) is the ambient temperature; \([R_d]^{n,n}\) is the thermal resistance matrix of multi-heat source components, which can be expressed as:

\[
[R_d]^{n,n} = \begin{bmatrix} R_{11} & \cdots & R_{1l} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ R_{l1} & \cdots & R_{ll} & \cdots & R_{ln} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ R_{n1} & \cdots & R_{nl} & \cdots & R_{nn} \end{bmatrix}
\]  

(13)

When \( i = l \), \( R_{il} \) is the self-heating resistance of heat source \( i \). When \( i \neq l \), \( R_{il} \) is the coupled thermal resistance of heat source \( L \) to heat source \( I \). The expression of \( R_{il} \) is:

\[ R_{il} = \frac{\Delta T_{i\rightarrow a}}{Q_i} = \frac{T_i - T_a}{Q_i} \]  

(14)

Where \( \Delta T_{i\rightarrow a} \) is the temperature rise of heat source \( i \) relative to the ambient temperature caused by heat source \( I \); \( T_i \) is the temperature of heat source \( I \) when heat source \( I \) is working; \( Q_i \) is the heating power of heat source \( I \).

In summary, the theoretical calculated value of the cold end temperature of each thermoelectric refrigerating sheet is:

\[
T_c = \frac{1}{S_mI} \left( kP + b + \frac{1}{2}I^2R_m - \frac{K_m}{S_mI(S_mI\Delta T_{il} - E)} - EK_m \right) \left( (S_mIR_{il} - E)(kP + b) \right. \\
+ (S_mIR_{il} - E)NI^2R_m + S_mI\Delta T_a + \left. \frac{1}{2}I^2R_m \right)
\]  

(15)

Where, \( E \) is the four-dimensional identity matrix, and \( N \) is the column vector \([1;1;1;1]\).

4. Results and Discussion

Some simulation results and theoretical calculation results are shown in Fig. 5 below.
It can be seen from the figure that the simulation results are in good agreement with the theoretical calculation results in various cases.

5. conclusion
In this paper, using the classical model of thermoelectric refrigerating sheet and the thermal resistance matrix method, a method of theoretical calculation is proposed for the working performance parameters of the refrigeration module of the multi-thermoelectric refrigeration chip, that is, the cold end temperature of the thermoelectric refrigeration plate. Taking the DA-type thermoelectric refrigeration module of four thermoelectric refrigeration sheets as an example, the theoretical calculation results and finite element simulation results based on FlotherM are compared. The results showed that: there is little difference between the results obtained by the above theoretical calculation method and those obtained by the simulation. When the heating power of the heat source is 50W, the maximum difference between the two results is only 5.83%, so this method is considered acceptable.

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